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(54) Title: OBFUSCATION TECHNIQUES FOR ENHANCING SOFTWARE SECURITY		
(57) Abstract <p>The present invention provides obfuscation techniques for enhancing software security. In one embodiment, a method for obfuscation techniques for enhancing software security includes selecting a subset of code (e.g., compiled source code of an application) to obfuscate, and obfuscating the selected subset of the code. The obfuscating includes applying an obfuscating transformation to the selected subset of the code. The transformed code can be weakly equivalent to the untransformed code. The applied transformation can be selected based on a desired level of security (e.g., resistance to reverse engineering). The applied transformation can include a control transformation that can be creating using opaque constructs, which can be constructed using aliasing and concurrency techniques. Accordingly, the code can be obfuscated for enhanced software security based on a desired level of obfuscation (e.g., based on a desired potency, resilience, and cost).</p>		

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OBFUSCATION TECHNIQUES FOR ENHANCING SOFTWARE SECURITY

5 FIELD OF THE INVENTION

The present invention relates to methods and apparatus for preventing, or at least hampering, interpretation, decoding, or reverse engineering of software. More particularly, although not exclusively,
10 the present invention relates to methods and apparatus for increasing the structural and logical complexity of software by inserting, removing, or rearranging identifiable structure or information from the software in such a way as to exacerbate the difficulty of the
15 process of decompilation or reverse engineering.

BACKGROUND

The nature of software renders it susceptible to analysis and copying by third parties. There have been
20 considerable efforts to enhance software security, which have met with mixed success. Such security concerns relate to the need to prevent unauthorized copying of software and a desire to conceal programming techniques in which such techniques can be determined
25 via reverse engineering.

Established legal avenues, such as copyright, provide a measure of legislative protection. However, enforcing legal rights created under such regimes can be expensive and time consuming. Further, the
30 protection afforded to software under copyright does

not cover programming techniques. Such techniques (i.e., the function as opposed to the form of the software) are legally difficult to protect. A reverse engineer could escape infringement by rewriting the relevant software, ab initio, based on a detailed knowledge of the function of the software in question. Such knowledge can be derived from analyzing the data structures, abstractions, and organization of the code.

Software patents provide more comprehensive protection. However, it is clearly an advantage to couple legal protection of software with technical protection.

Previous approaches to the protection of proprietary software have either used encryption-based hardware solutions or have been based on simple rearrangements of the source code structure. Hardware-based techniques are non-ideal in that they are generally expensive and are tied to a specific platform or hardware add-on. Software solutions typically include trivial code obfuscators, such as the Crema obfuscator for Java™. Some obfuscators target the lexical structure of the application and typically remove source code formatting and comments and rename variables. However, such an obfuscation technique does not provide sufficient protection against malicious reverse engineering: reverse engineering is a problem regardless of the form in which the software is distributed. Further, the problem is exacerbated when the software is distributed in hardware-independent formats that retain much or all of the information in

the original source code. Examples of such formats are Java™ bytecode and the Architecture Neutral Distribution Format (ANDF).

Software development can represent a significant investment in time, effort, and skill by a programmer. In the commercial context, the ability to prevent a competitor from copying proprietary techniques can be critical.

10 SUMMARY

The present invention provides methods and apparatus for obfuscation techniques for software security, such as computer implemented methods for reducing the susceptibility of software to reverse engineering (or to provide the public with a useful choice). In one embodiment, a computer implemented method for obfuscating code, includes testing for completion of supplying one or more obfuscation transformations to the code, selecting a subset of the code to obfuscate, selecting an obfuscating transform to apply, applying the transformation, and returning to the completion testing step.

In an alternative embodiment, the present invention relates to a method of controlling a computer so that software running on, stored on, or manipulated by the computer exhibits a predetermined and controlled degree of resistance to reverse engineering, including applying selected obfuscating transformations to selected parts of the software, in which a level of obfuscation is achieved using a selected obfuscation

transformation so as to provide a required degree of resistance to reverse engineering, effectiveness in operation of the software and size of transformed software, and updating the software to reflect the
5 obfuscating transformations.

In a preferred embodiment, the present invention provides a computer implemented method for enhancing software security, including identifying one or more source code input files corresponding to the source
10 software for the application to be processed, selecting a required level of obfuscation (e.g., potency), selecting a maximum execution time or space penalty (e.g., cost), reading and parsing the input files, optionally along with any library or supplemental files
15 read directly or indirectly by the source code, providing information identifying data types, data structures, and control structures used by the application to be processed, and constructing appropriate tables to store this information,
20 preprocessing information about the application, in response to the preprocessing step, selecting and applying obfuscating code transformations to source code objects, repeating the obfuscating code transformation step until the required potency has been
25 achieved or the maximum cost has been exceeded, and outputting the transformed software.

Preferably, the information about the application is obtained using various static analysis techniques and dynamic analysis techniques. The static analysis
30 techniques include inter-procedural dataflow analysis

and data dependence analysis. The dynamic analysis techniques include profiling, and optionally, information can be obtained via a user. Profiling can be used to determine the level of obfuscation, which
5 can be applied to a particular source code object. Transformations can include control transformations created using opaque constructs in which an opaque construct is any mathematical object that is inexpensive to execute from a performance standpoint,
10 simple for an obfuscator to construct, and expensive for a deobfuscator to break. Preferably, opaque constructs can be constructed using aliasing and concurrency techniques. Information about the source application can also be obtained using pragmatic
15 analysis, which determines the nature of language constructs and programming idioms the application contains.

The potency of an obfuscation transformation can be evaluated using software complexity metrics.
20 Obfuscation code transformations can be applied to any language constructs: for example, modules, classes, or subroutines can be split or merged; new control and data structures can be created; and original control and data structures can be modified. Preferably, the
25 new constructs added to the transformed application are selected to be as similar as possible to those in the source application, based on the pragmatic information gathered during preprocessing. The method can produce subsidiary files including information about which
30 obfuscating transformations have been applied and

information relating obfuscated code of the transformed application to the source software.

Preferably, the obfuscation transformations are selected to preserve the observable behavior of the software such that if P is the untransformed software, and P' is the transformed software, P and P' have the same observable behavior. More particularly, if P fails to terminate or terminates with an error condition, then P' may or may not terminate, otherwise P' terminates and produce the same output as P. Observable behavior includes effects experienced by a user, but P and P' may run with different detailed behavior unobservable by a user. For example, detailed behavior of P and P' that can be different includes file creation, memory usage, and network communication.

In one embodiment, the present invention also provides a deobfuscating tool adopted to remove obfuscations from an obfuscated application by use of slicing, partial evaluation, dataflow analysis, or statistical analysis.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will now be described by way of example only and with reference to the drawings in which:

FIG. 1 illustrates a data processing system in accordance with the teachings of the present invention;

FIG. 2 illustrates a classification of software protection including categories of obfuscating transformations;

FIGs. 3a and 3b show techniques for providing software security by (a) server-side execution and (b) partial server-side execution;

FIGs. 4a and 4b show techniques for providing software security by (a) using encryption and (b) using signed native code;

FIG. 5 shows a technique for providing software security through obfuscation;

FIG. 6 illustrates the architecture of an example of an obfuscating tool suitable for use with Java™ applications;

FIG. 7 is a table that tabulates a selection of known software complexity metrics;

FIGs. 8a and 8b illustrate the resilience of an obfuscating transformation;

FIG. 9 shows different types of opaque predicates;

FIGs. 10a and 10b provide examples of (a) trivial opaque constructs and (b) weak opaque constructs;

FIG. 11 illustrates an example of a computation transformation (branch insertion transformation);

FIGs. 12a through 12d illustrate a loop condition insertion transformation;

FIG. 13 illustrates a transformation that transforms reducible flowgraphs into non-reducible flowgraphs;

FIG. 14 shows that a section of code can be parallelized if it contains no data dependencies;

FIG. 15 shows that a section of code that contains no data dependencies can be split into concurrent

threads by inserting appropriate synchronization primitives;

FIG. 16 shows how procedures P and Q are inlined at their call-sites and then removed from the code;

5 FIG. 17 illustrates inlining method calls;

FIG. 18 shows a technique for interleaving two methods declared in the same class;

FIG. 19 shows a technique for creating several different versions of a method by applying different sets of obfuscating transformations to the original code;

10

FIGS. 20a through 20c provide examples of loop transformations including (a) loop blocking, (b) loop unrolling, and (c) loop fission;

15 FIG. 21 shows a variable splitting example;

FIG. 22 provides a function constructed to obfuscate strings "AAA", "BAAAA", and "CCB";

FIG. 23 shows an example merging two 32-bit variables x and y into one 64-bit variable Z;

20 FIG. 24 illustrates an example of a data transformation for array restructuring;

FIG. 25 illustrates modifications of an inheritance hierarchy;

FIG. 26 illustrates opaque predicates constructed from objects and aliases;

25

FIG. 27 provides an example of opaque constructs using threads;

FIGS. 28a through 28d illustrate obfuscation vs. deobfuscation in which (a) shows an original program including three statements, $S_{1..3}$, being obfuscated, (b)

30

shows a deobfuscator identifying "constant" opaque predicates, (c) shows the deobfuscator determining the common code in the statements, and (d) shows the deobfuscator applying some final simplifications and
5 returning the program to its original form;

FIG. 29 shows an architecture of a JavaTM deobfuscation tool;

FIG. 30 shows an example of statistical analysis used for evaluation;

10 FIGs. 31a and 31b provide tables of an overview of various obfuscating transforms; and

FIG. 32 provides an overview of various opaque constructs.

15 DETAILED DESCRIPTION

The following description will be provided in the context of a JavaTM obfuscation tool, which is currently being developed by the applicants. However, it will be apparent to one of ordinary skill in the art that the
20 present techniques are applicable to other programming languages and the invention is not to be construed as restricted to JavaTM applications. The implementation of the present invention in the context of other programming languages is considered to be within the
25 purview of one of ordinary skill in the art. The exemplary embodiment that follows is, for clarity, specifically targeted at a JavaTM obfuscating tool.

In the description below, the following nomenclature will be used. P is the input application
30 to be obfuscated; P' is the transformed application; T

is a transformation such that T transforms P into P' .
 $P(T)P'$ is an obfuscating transformation if P and P'
have the same observable behavior. Observable behavior
is defined generally as behavior experienced by the
5 user. Thus, P' may have side effects such as creating
files that P does not, so long as these side effects
are not experienced by the user. P and P' do not need
to be equally efficient.

10

Exemplary Hardware

FIG. 1 illustrates a data processing system in
accordance with the teachings of the present invention.
FIG. 1 shows a computer 100, which includes three major
elements. Computer 100 includes an input/output (I/O)
15 circuit 120, which is used to communicate information
in appropriately structured form to and from other
portions of computer 100. Computer 100 includes a
control processing unit (CPU) 130 in communication with
I/O circuit 120 and a memory 140 (e.g., volatile and
20 non-volatile memory). These elements are those
typically found in most general purpose computers and,
in fact, computer 100 is intended to be representative
of a broad category of data processing devices. A
raster display monitor 160 is shown in communication
25 with I/O circuit 120 and issued to display images
generated by CPU 130. Any well known variety of
cathode ray tube (CRT) or other type of display can be
used as display 160. A conventional keyboard 150 is
also shown in communication with I/O 120. It will be
30 appreciated by one of ordinary skill in the art that

computer 100 can be part of a larger system. For example, computer 100 can also be in communication with a network (e.g., connected to a local area network (LAN)).

5 In particular, computer 100 can include obfuscating circuitry for enhancing software security in accordance with the teachings of the present invention, or as will be appreciated by one of ordinary skill in the art, the present invention can be
10 implemented in software executed by computer 100 (e.g., the software can be stored in memory 140 and executed on CPU 130). For example, an unobfuscated program P (e.g., an application), stored in memory 140, can be obfuscated by an obfuscator executing on CPU 130 to
15 provide an obfuscated program P', stored in memory 140, in accordance with one embodiment of the present invention.

Overview of the Detailed Description

20 FIG. 6 shows the architecture of a Java™ obfuscator. According to the inventive method, Java™ application class files are passed along with any library files. An inheritance tree is constructed as well as a symbol table, providing type information for
25 all symbols and control flow graphs for all methods. The user may optionally provide profiling data files as generated by Java™ profiling tools. This information can be used to guide the obfuscator to ensure that
30 obfuscated by very expensive transformations.

Information is gathered about the application using standard compiler techniques such as interprocedural dataflow analysis and data dependence analysis. Some can be provided by the user and some by specialized
5 techniques. The information is used to select and apply the appropriate code transformations.

Appropriate transformations are selected. The governing criteria used in selecting the most suitable transformation include the requirement that the chosen
10 transformation blend in naturally with the rest of the code. This can be dealt with by favoring transformations with a high appropriateness value. A further requirement is that transformations which yield a high level of obfuscation with low execution time
15 penalty should be favored. This latter point is accomplished by selecting transformations that maximize potency and resilience, and minimize cost.

An obfuscation priority is allocated to a source code object. This will reflect how important it is to
20 obfuscate the contents of the source code object. For example, if a particular source code object contains highly sensitive proprietary material, then the obfuscation priority will be high. An execution time rank is determined for each method, which equals 1 if
25 more time is spent executing the method than any other.

The application is then obfuscated by building the appropriate internal data structures, the mapping from each source code object to the appropriate transformation, the obfuscation priority, and the
30 execution time rank. The obfuscating transformations

are applied until the required level of obfuscation has been achieved or until the maximum execution time penalty is exceeded. The transformed application is then written.

5 The output of the obfuscation tool is a new application that is functionally equivalent to the original. The tool can also produce Java™ source files annotated with information about which transformations have been applied and how the obfuscated code relates
10 to the original application.

A number of examples of obfuscating transformations will now be described, again in the context of a Java™ obfuscator.

Obfuscating transformations can be evaluated and
15 classified according to their quality. The quality of a transformation can be expressed according to its potency, resilience, and cost. The potency of a transformation is related to how obscure P' is in relation to P. Any such metric will be relatively
20 vague as it necessarily depends on human cognitive abilities. For the present purposes it is sufficient to consider the potency of a transformation as a measure of the usefulness of the transformation. The resilience of a transformation measures how well a
25 transformation holds up to an attack from an automatic deobfuscator. This is a combination of two factors: programmer effort and deobfuscator effort. Resilience can be measured on a scale from trivial to one-way. One-way transformations are extreme in that they cannot
30 be reversed. The third component is transformation

execution cost. This is the execution time or space penalty incurred as a result of using the transformed application P'. Further details of transformation evaluation are discussed below in the detailed
5 description of the preferred embodiments. The main classification of obfuscating transformations is shown in FIG. 2c with details given in FIGs. 2e through 2g.

Examples of obfuscating transforms are as follows:
Obfuscating transforms may be categorized as follows:
10 control obfuscation, data obfuscations, layout obfuscations, and preventive obfuscations. Some examples of these are discussed below.

Control obfuscations include aggregation transformations, ordering transformations, and
15 computation transformations.

Computation transformations include: concealing real control flow behind irrelevant non-functional statements; introducing code sequences at the object code level for which there exist no corresponding high-
20 level language constructs; and removing real control flow abstractions or introducing spurious ones.

Considering the first classification (control flow), the Cyclomatic and Nesting complexity metrics suggest that there is a strong correlation between the
25 perceived complexity of a piece of code and the number of predicates it contains. Opaque predicates enable the construction of transformations which introduce new predicates into the program.

Referring to FIG. 11a, an opaque predicate P^T is
30 inserted into the basic block S where $S = S_1 \dots S_n$. This

splits S in half. The P^T predicate is irrelevant code, because it will always evaluate to True. In FIG. 11b, S is again broken into two halves, which are transformed into two different obfuscated versions S^a and S^b . Therefore, it will not be obvious to a reverse engineer that S^a and S^b perform the same function. FIG. 11c is similar to FIG. 11b, however, a bug is introduced into S^b . The P^T predicate always selects the correct version of the code, S^a .

Another type of obfuscation transformation is a data transformation. An example of a data transformation is deconstructing arrays to increase the complexity of code. An array can be split into several subarrays, two or more arrays can be merged into a single array, or the dimensions of an array can be increased (flattening) or decreased (folding). FIG. 24 illustrates a number of examples of array transformations. In statements (1-2), an array A is split into two subarrays $A1$ and $A2$. $A1$ contains elements with even indices and $A2$ contains elements with odd indices. Statements (3-4) illustrate how two integer arrays B and C can be interleaved to produce an array BC . The elements from B and C are evenly spread throughout the transformed array. Statements (6-7) illustrate folding of array D into array $D1$. Such transformations introduce previously absent data structure or remove existing data structure. This can greatly increase the obscurity of the program as, for example, in declaring a 2-dimensional array a programmer usually does so for a purpose, with the

chosen structure mapping onto the corresponding data.
If that array is folded into a 1-d structure, a reverse engineer would be deprived of valuable pragmatic information.

5 Another example of an obfuscating transformation is a preventive transformation. In contrast to control or data transformations, the main goal of preventive transformations is not to obscure the program to a human reader, but to make known automatic deobfuscation
10 techniques more difficult or to exploit known problems in current deobfuscators or decompilers. Such transformations are known as inherent and targeted, respectively. An example of an inherent preventive transformation is reordering a for-loop to run
15 backward. Such reordering is possible if the loop has no loop-carried data dependencies. A deobfuscator could perform the same analysis and reorder the loop to forward execution. However, if a bogus data dependency is added to the reversed loop, the identification of
20 the loop and its reordering would be prevented.

Further specific examples of obfuscating transformations are discussed below in the detailed description of the preferred embodiments.

25 Detailed Description of the Preferred Embodiments

It has become more and more common to distribute software in forms that retain most or all of the information present in the original source code. An important example is Java
30 bytecode. Because such codes are easy to

decompile, they increase the risk of malicious reverse engineering attacks.

Accordingly, several techniques for technical protection of software secrets are provided in accordance with one embodiment of the present invention. In the detailed description of the preferred embodiments, we will argue that automatic code obfuscation is currently the most viable method for preventing reverse engineering. We then describe the design of a code obfuscator, an obfuscation tool that converts a program into an equivalent one that is more difficult to understand and reverse engineer.

The obfuscator is based on the application of code transformations, in many cases similar to those used by compiler optimizers. We describe a large number of such transformations, classify them, and evaluate them with respect to their potency (e.g., To what degree is a human reader confused?), resilience (e.g., How well are automatic deobfuscation attacks resisted?), and cost (e.g., How much performance overhead is added to the application?).

We finally describe various deobfuscation techniques (such as program slicing) and possible countermeasures an obfuscator could employ against them.

1 Introduction

Given enough time, effort, and determination, a competent programmer will always be able to reverse engineer any application. Having gained physical access to the application, the reverse engineer can decompile it (using disassemblers or
5 decompilers) and then analyze its data structures and control flow. This can either be done manually or with the aid of reverse engineering tools, such as program slicers.

10 Reverse engineering is not a new problem. Until recently, however, it is a problem that has received relatively little attention from software developers, because most programs are large, monolithic, and shipped as stripped, native code,
15 making them difficult (although never impossible) to reverse engineer.

However, this situation is changing as it is becoming more and more common to distribute software in forms that are easy to decompile and
20 reverse engineer. Important examples include Java bytecode and the Architecture Neutral Distribution Format (ANDF). Java applications in particular pose a problem to software developers. They are distributed over the Internet as Java class files,
25 a hardware-independent virtual machine code that retains virtually all the information of the original Java source. Hence, these class files are easy to decompile. Moreover, because much of the computation takes place in standard libraries,

Java programs are often small in size and therefore relatively easy to reverse engineer.

The main concern of Java developers is not outright reengineering of entire applications.

5 There is relatively little value in such behavior, because it clearly violates copyright law [29] and can be handled through litigation. Rather, developers are mostly frightened by the prospect of a competitor being able to extract proprietary
10 algorithms and data structures from their applications in order to incorporate them into their own programs. Not only does it give the competitor a commercial edge (by cutting development time and cost), but it is also
15 difficult to detect and pursue legally. The last point is particularly valid for small developers who may ill afford lengthy legal battles against powerful corporations [22] with unlimited legal budgets.

20 An overview of various forms of protection for providing legal protection or security for software is provided in FIG. 2. FIG. 2 provides a classification of (a) kinds of protection against malicious reverse engineering, (b) the quality of
25 an obfuscating transformation, (c) information targeted by an obfuscating transformation, (d) layout obfuscations, (e) data obfuscations, (f) control obfuscations, and (g) preventive obfuscations.

The various forms of technical protection of intellectual property, which are available to software developers are discussed below. We will restrict our discussion to Java programs distributed over the Internet as Java class-files, although most of our results will apply to other languages and architecture-neutral formats as well, as will be apparent to one of ordinary skill in the art. We will argue that the only reasonable approach to the protection of mobile code is code obfuscation. We will furthermore present a number of obfuscating transformations, classify them according to effectiveness and efficiency, and show how they can be put to use in an automatic obfuscation tool.

The remainder of the detailed description of the preferred embodiments is structured as follows. In Section 2, we give an overview of different forms of technical protection against software theft and argue that code obfuscation currently affords the most economical prevention. In Section 3, we give a brief overview of the design of Kava, a code obfuscator for Java, which is currently under construction. Sections 4 and 5 describe the criteria we use to classify and evaluate different types of obfuscating transformations. Sections 6, 7, 8, and 9 present a catalogue of obfuscating transformations. In Section 10, we give more detailed obfuscation algorithms. In Section 11, we conclude with a

summary of our results and a discussion of future directions of code obfuscation.

2 Protecting Intellectual Property

5 Consider the following scenario. Alice is a small software developer who wants to make her applications available to users over the Internet, presumably at a charge. Bob is a rival developer who feels that he could gain a commercial edge
10 over Alice if he had access to her application's key algorithms and data structures.

 This can be seen as a two-player game between two adversaries: the software developer (Alice) who tries to protect her code from attack, and the
15 reverse engineer (Bob) whose task it is to analyze the application and convert it into a form that is easy to read and understand. Note that it is not necessary for Bob to convert the application back to something close to Alice's original source; all
20 that is necessary is that the reverse engineered code be understandable by Bob and his programmers. Note also that it may not be necessary for Alice to protect her entire application from Bob; it probably consists mostly of "bread-and-butter
25 code" that is of no real interest to a competitor.

 Alice can protect her code from Bob's attack using either legal or technical protection, such as shown in FIG. 2a, which is discussed above. While copyright law does cover software artifacts,
30 economic realities make it difficult for a small

company like Alice's to enforce the law against a larger and more powerful competitor. A more attractive solution is for Alice to protect her code by making reverse engineering so technically
5 difficult that it becomes impossible or at the very least economically inviable. Some early attempts at technical protection are described by Gosler. (James R. Gosler. Software protection: Myth or reality? In CRYPTO'85 --- Advances in
10 Cryptology, pages 140--157, August 1985).

The most secure approach is for Alice not to sell her application at all, but rather sell its services. In other words, users never gain access to the application itself but rather connect to
15 Alice's site to run the program remotely as shown in FIG. 3a, paying a small amount of electronic money every time. The advantage to Alice is that Bob will never gain physical access to the application and hence will not be able to reverse
20 engineer it. The downside is of course that, due to limits on network bandwidth and latency, the application may perform much worse than if it had run locally on the user's site. A partial solution is to break the application into two
25 parts: a public part that runs locally on the user's site, and a private part (that contains the algorithms that Alice wants to protect) that is run remotely, for example, as shown in FIG. 3b.

Another approach would be for Alice to
30 encrypt her code before it is sent off to the

users, for example, as shown in FIG. 4a.
Unfortunately, this only works if the entire
decryption/execution process takes place in
hardware. Such systems are described in Herzberg
5 (Amir Herzberg and Shlomit S. Pinter. Public
protection of software. ACM Transactions on
Computer Systems, 5(4):371--393, November 1987.)
and Wilhelm (Uwe G. Wilhelm. Cryptographically
protected objects.
10 <http://lsewww.epfl.ch/~wilhelm/CryPO.html>, 1997).
If the code is executed in software by a virtual
machine interpreter (as is most often the case
with Java bytecodes), then it will always be
possible for Bob to intercept and decompile the
15 decrypted code.

The Java™ programming language has gained
popularity mainly because of its architecture
neutral bytecode. While this clearly facilitates
mobile code, it does decrease the performance by
20 an order of magnitude in comparison to native
code. Predictably, this has lead to the
development of just-in-time compilers that
translate Java bytecodes to native code
on-the-fly. Alice could make use of such
25 translators to create native code versions of her
application for all popular architectures. When
downloading the application, the user's site would
have to identify the architecture/operating system
combination it is running, and the corresponding
30 version would be transmitted, for example, as

shown in FIG. 4b. Only having access to the native code will make Bob's task more difficult, although not impossible. There is a further complication with transmitting

5 native code. The problem is that --- unlike Java bytecodes, which are subjected to bytecode verification before execution, --- native codes cannot be run with complete security on the user's machine. If Alice is a trusted member of the

10 community, the user may accept her assurances that the application does not do anything harmful at the user's end. To make sure that no one tries to contaminate the application, Alice would have to digitally sign the codes as they are being

15 transmitted, to prove to the user that the code was the original one written by her.

The final approach we are going to consider is code obfuscation, for example, as shown in FIG. 5. The basic idea is for Alice to run her

20 application through an obfuscator, a program that transforms the application into one that is functionally identical to the original but which is much more difficult for Bob to understand. It is our belief that obfuscation is a viable

25 technique for protecting software trade secrets that has yet to receive the attention that it deserves.

Unlike server-side execution, code obfuscation can never completely protect an

30 application from malicious reverse engineering

efforts. Given enough time and determination, Bob will always be able to dissect Alice's application to retrieve its important algorithms and data structures. To aid this effort, Bob may try to run
5 the obfuscated code through an automatic deobfuscator that attempts to undo the obfuscating transformations.

Hence, the level of security from reverse engineering that an obfuscator adds to an
10 application depends on, for example, (a) the sophistication of the transformations employed by the obfuscator, (b) the power of the available deobfuscation algorithms, and (c) the amount of resources (time and space) available to the
15 deobfuscator. Ideally, we would like to mimic the situation in current public-key cryptosystems, in which there is a dramatic difference in the cost of encryption (finding large primes is easy) and decryption (factoring large numbers is difficult).
20 We will see that there are, in fact, obfuscating transformations that can be applied in polynomial time but which require exponential time to deobfuscate, as discussed below.

25 3 The Design of a Java Obfuscator

FIG. 6 shows an architecture of Kava, the Java obfuscator. The main input to the tool is a set of Java class files and the obfuscation level required by the user. The user may optionally
30 provide files of profiling data, as generated by

Java profiling tools. This information can be used to guide the obfuscator to make sure that frequently executed parts of the application are not obfuscated by very expensive transformations.

5 Input to the tool is a Java application, given as a set of Java class files. The user also selects the required level of obfuscation (e.g., potency) and the maximum execution time/space penalty that the obfuscator is allowed to add to the

10 application (the cost). Kava reads and parses the class files along with any library files referenced directly or indirectly. A complete inheritance tree is constructed, as well as a symbol table giving type information for all

15 symbols, and control flow graphs for all methods.

Kava contains a large pool of code transformations, which are described below. Before these can be applied, however, a preprocessing pass collects various types of

20 information about the application in accordance with one embodiment. Some kinds of information can be gathered using standard compiler techniques such as inter-procedural dataflow analysis and data dependence analysis, some can be provided by

25 the user, and some are gathered using specialized techniques. Pragmatic analysis, for example, analyzes the application to see what sort of language constructs and programming idioms it contains.

The information gathered during the preprocessing pass is used to select and apply appropriate code transformations. All types of language constructs in the application can be the subject of obfuscation: for example, classes can be split or merged, methods can be changed or created, new control and data structures can be created and original ones modified. New constructs added to the application can be selected to be as similar as possible to the ones in the source application, based on the pragmatic information gathered during the preprocessing pass.

The transformation process is repeated until the required potency has been achieved or the maximum cost has been exceeded. The output of the tool is a new application -- functionally equivalent to the original one -- normally given as a set of Java class files. The tool will also be able to produce Java source files annotated with information about which transformations have been applied, and how the obfuscated code relates to the original source. The annotated source will be useful for debugging.

4 Classifying Obfuscating Transformations

In the remainder of this detailed description of the preferred embodiments we will describe, classify, and evaluate various obfuscating transformations. We start by formalizing the notion of an obfuscating transformation:

Definition 1 (Obfuscating Transformation)

Let $P \xrightarrow{T} P'$ be a legal obfuscating transformation
in which the following conditions must hold:

5

- If P fails to terminate or terminates with
an error condition, then P' may or may not
terminate.

10

- Otherwise, P' must terminate and produce
the same output as P .

Observable behavior is defined loosely as
"behavior as experienced by the user." This means
15 that P' may have side-effects (such as creating
files or sending messages over the Internet) that
 P does not, as long as these side effects are not
experienced by the user. Note that we do not
require P and P' to be equally efficient. In fact,
20 many of our transformations will result in P'
being slower or using more memory than P .

The main dividing line between different
classes of obfuscation techniques is shown in FIG.
2c. We primarily classify an obfuscating
25 transformation according to the kind of
information it targets. Some simple
transformations target the lexical structure (the
layout) of the application, such as source code
formatting, and names of variables. In one
30 embodiment, the more sophisticated transformations

that we are interested in, target either the data structures used by the application or its flow of control.

Secondly, we classify a transformation
5 according to the kind of operation it performs on the targeted information. As can be seen from FIGs. 2d through 2g, there are several transformations that manipulate the aggregation of control or data. Such transformations typically
10 break up abstractions created by the programmer, or construct new bogus abstractions by bundling together unrelated data or control.

Similarly, some transformations affect the ordering of data or control. In many cases the
15 order in which two items are declared or two computations are performed has no effect on the observable behavior of the program. There can, however, be much useful information embedded in the chosen order, to the programmer who wrote the
20 program as well as to a reverse engineer. The closer two items or events are in space or time, the higher the likelihood that they are related in one way or another. Ordering transformations try to explore this by randomizing the order of
25 declarations or computations.

5 Evaluating Obfuscating Transformations

Before we can attempt to design any obfuscating transformations, we should be able to
30 evaluate the quality of such a transformation. In

this section we will attempt to classify transformations according to several criteria: how much obscurity they add to the program (e.g., potency), how difficult they are to break for a deobfuscator (e.g., resilience), and how much computational overhead they add to the obfuscated application (e.g., cost).

5.1 Measures of Potency

10 We will first define what it means for a program P' to be more obscure (or complex or unreadable) than a program P . Any such metric will, by definition, be relatively vague, because it must be based (in part) on human cognitive
15 abilities.

 Fortunately, we can draw upon the vast body of work in the Software Complexity Metrics branch of Software Engineering. In this field, metrics are designed with the intent to aid the
20 construction of readable, reliable, and maintainable software. The metrics are frequently based on counting various textual properties of the source code and combining these counts into a measure of complexity. While some of the formulas
25 that have been proposed have been derived from empirical studies of real programs, others have been purely speculative.

 The detailed complexity formulas found in the metrics' literature can be used to derive general
30 statements, such as: "if programs P and P' are

identical except that P' contains more of property q than P , then P' is more complex than P ." Given such a statement, we can attempt to construct a transformation that adds more of the q -property to
5 a program, knowing that this is likely to increase its obscurity.

FIG. 7 is a table that tabulates some of the more popular complexity measures, in which $E(x)$ is the complexity of a software component x , F is a
10 function or method, C is a class, and P is a program. When used in a software construction project the typical goal is to minimize these measures. In contrast, when obfuscating a program we generally want to maximize the measures.

15 The complexity metrics allow us to formalize the concept of potency and will be used below as a measure of the usefulness of a transformation. Informally, a transformation is potent if it does a good job confusing Bob, by hiding the intent of
20 Alice's original code. In other words, the potency of a transformation measures how much more difficult the obfuscated code is to understand (for a human) than the original code. This is formalized in the following definition:

25
Definition 2 (Transformation Potency) Let T be a behavior-conserving transformation, such that $P \xrightarrow{T} P'$ transforms a source program P into a target program P' . Let $E(P)$ be the complexity of
30 P , as defined by one of the metrics of FIG. 7.

$T_{\text{pot}}(P)$, the potency of T with respect to a program P , is a measure of the extent to which T changes the complexity of P . It is defined as

$$T_{\text{pot}}(P) \stackrel{\text{def}}{=} E(P')/E(P) - 1.$$

- 5 T is a potent obfuscating transformation if
 $T_{\text{pot}}(P) > 0$.

For the purposes of this discussion, we will measure potency on a three-point scale, (low,
 10 medium, high).

The observations in Table 1 make it possible for us to list some desirable properties of a transformation T . In order for T to be a potent obfuscating transformation, it should

- 15 - increase overall program size (u_1) and introduce new classes and methods (u^a_7).
- introduce new predicates (u_2) and increase the nesting level of conditional and looping constructs
- 20 (u_3).
- increase the number of method arguments (u_5) and inter-class instance variable dependencies (u^d_7).
- increase the height of the inheritance tree ($u^{b,c}_7$).
- 25 - increase long-range variable dependencies (u_4).

5.2 Measures of Resilience

At first glance it would seem that increasing $T_{\text{pot}}(P)$ would be trivial. To increase the u_2 metric, for example, all we have to do is to add
 5 some arbitrary if-statements to P:

	main() {		main() {
	S1;		S1;
	S2;	$\stackrel{T}{=}\Rightarrow$	if (5==2) S1;
10			S2;}
			if (1>2) S2;
			}

Unfortunately, such transformations are
 15 virtually useless, because they can easily be undone by simple automatic techniques. It is therefore necessary to introduce the concept of resilience, which measures how well a transformation holds up under attack from an
 20 automatic deobfuscator. For example, the resilience of a transformation T can be seen as the combination of two measures:

Programmer Effort: the amount of time
 25 required to construct an automatic deobfuscator that is able to effectively reduce the potency of T , and

Deobfuscator Effort: the execution time and
 30 space required by such an automatic

deobfuscator to effectively reduce the
potency of T .

It is important to distinguish between
5 resilience and potency. A transformation is potent
if it manages to confuse a human reader, but it is
resilient if it confuses an automatic
deobfuscator.

We measure resilience on a scale from trivial
10 to one way, as shown in FIG. 8a. One-way
transformations are special, in the sense that
they can never be undone. This is typically
because they remove information from the program
that was useful to the human programmer, but which
15 is not necessary in order to execute the program
correctly. Examples include transformations that
remove formatting, and scramble variable names.

Other transformations typically add useless
information to the program that does not change
20 its observable behavior, but which increases the
"information load" on a human reader. These
transformations can be undone with varying degrees
of difficulty.

FIG. 8b shows that deobfuscator effort is
25 classified as either polynomial time or
exponential time. Programmer effort, the work
required to automate the deobfuscation of a
transformation T, is measured as a function of the
scope of T. This is based on the intuition that
30 it is easier to construct counter-measures against

an obfuscating transformation that only affects a small part of a procedure, than against one that may affect an entire program.

The scope of a transformation is defined using terminology borrowed from code optimization theory: T is a local transformation if it affects a single basic block of a control flow graph (CFG), it is global if it affects an entire CFG, it is inter-procedural if it affects the flow of information between procedures, and it is an interprocess transformation if it affects the interaction between independently executing threads of control.

Definition 3 (Transformation Resilience) Let T be a behavior-conserving transformation, such that $P \xrightarrow{T} P'$ transforms a source program P into a target program P'. $T_{res}(P)$ is the resilience of T with respect to a program P.

$T_{res}(P)$ is a one-way transformation if information is removed from P such that P cannot be reconstructed from P'. Otherwise,

$$T_{res}^{def} = \text{Resilience}(T_{\text{Deobfuscator effort}}, T_{\text{Programmer effort}}),$$

in which Resilience is the function defined in the matrix in FIG. 8b.

5.3 Measures of Execution Cost

In FIG. 2b, we see that potency and resilience are two of the three components

describing the quality of a transformation. The third component, the cost of a transformation, is the execution time or space penalty that a transformation incurs on an obfuscated application. We classify the cost on a four-point scale (free, cheap, costly, dear), in which each point is defined below:

Definition 5 (Transformation Cost) Let T be a behavior-conserving transformation, such that $T_{\text{cost}}(P) \in \{\text{dear, costly, cheap, free}\}$ with $T_{\text{cost}}(P) = \text{free}$, if executing P' requires $O(1)$ more resources than P ; otherwise $T_{\text{cost}}(P) = \text{cheap}$, if executing P' requires $O(n)$ more resources than P ; otherwise $T_{\text{cost}}(P) = \text{costly}$, if executing P' requires $O(n^p)$, with $p > 1$, more resources than P ; otherwise $T_{\text{cost}}(P) = \text{dear}$ (i.e., executing P' requires exponentially more resources than P).

It should be noted that the actual cost associated with a transformation depends on the environment in which it is applied. For example, a simple assignment statement $a=5$ inserted at the top-most level of a program will only incur a constant overhead. The same statement inserted inside an inner loop will have a substantially higher cost. Unless noted otherwise, we always provide the cost of a transformation as if it had been applied at the outermost nesting level of the source program.

5.4 Measures of Quality

We can now give a formal definition of the quality of an obfuscating transformation:

5

Definition 6 (Transformation Quality)

$T_{\text{qual}}(P)$, the quality of a transformation T , is defined as the combination of the potency, resilience, and cost of T : $T_{\text{qual}}(P) = (T_{\text{pot}}(P),$

10 $T_{\text{res}}(P), T_{\text{cost}}(P))$.

5.5 Layout Transformations

Before we explore novel transformations, we will briefly consider the trivial layout

15 transformations, which, for example, are typical of current Java obfuscators such as Crema. (Hans Peter Van Vliet. Crema --- The Java obfuscator. <http://web.inter.nl.net/users/H.P.van.Vliet/crema.html>, January 1996) The first
20 transformation removes the source code formatting information sometimes available in Java class files. This is a one-way transformation, because once the original formatting is gone it cannot be recovered; it is a transformation with low
25 potency, because there is very little semantic content in formatting, and no great confusion is introduced when that information is removed; finally, this is a free transformation, because the space and time complexity of the application
30 is not affected.

Scrambling identifier names is also a one-way and free transformation. However, it has a much higher potency than formatting removal, because identifiers contain a great deal of pragmatic
5 information.

6 Control Transformations

In this and the next few sections we will present a catalogue of obfuscating
10 transformations. Some have been derived from well-known transformations used in other areas such as compiler optimization and software reengineering, others have been developed for the sole purpose of obfuscation, in accordance with
15 one embodiment of the present invention.

In this section we will discuss transformations that attempt to obscure the control-flow of the source application. As indicated in FIG. 2f, we classify these
20 transformations as affecting the aggregation, ordering, or computations of the flow of control. Control aggregation transformations break up computations that logically belong together or merge computations that do not. Control ordering
25 transformations randomize the order in which computations are carried out. Computation transformations can insert new (redundant or dead) code, or make algorithmic changes to the source application.

For transformations that alter the flow of control, a certain amount of computational overhead will be unavoidable. For Alice this means that she may have to choose between a highly efficient program, and one that is highly obfuscated. An obfuscator can assist her in this trade-off by allowing her to choose between cheap and expensive transformations.

10 6.1 Opaque Predicates

The real challenge when designing control-altering transformations is to make them not only cheap, but also resistant to attack from deobfuscators. To achieve this, many transformations rely on the existence of opaque variables and opaque predicates. Informally, a variable *V* is opaque if it has some property *q* that is known a priori to the obfuscator, but which is difficult for the deobfuscator to deduce. Similarly, a predicate *P* (a Boolean expression) is opaque if a deobfuscator can deduce its outcome only with great difficulty, while this outcome is well known to the obfuscator.

Being able to create opaque variables and predicates that are difficult for a deobfuscator to crack is a major challenge to a creator of obfuscation tools, and the key to highly resilient control transformations. We measure the resilience of an opaque variable or predicate (i.e., its resistance to deobfuscation attacks) on the same

scale as transformation resilience (i.e., trivial, weak, strong, full, one-way). Similarly, we measure the added cost of an opaque construct on the same scale as transformation cost (i.e., free, cheap, costly, dear).

Definition 7 (Opaque Constructs) A variable V is opaque at a point p in a program, if V has a property q at p , which is known at obfuscation time. We write this as V_p^q or V^q if p is clear from the context. A predicate P is opaque at p if its outcome is known at obfuscation time. We write P_p^F (P_p^T) if P always evaluates to False (True) at p , and $P_p^?$ if P sometimes evaluates to True and sometimes to False. Again, p will be omitted if clear from the context. FIG. 9 shows different types of opaque predicates. Solid lines indicate paths that may sometimes be taken, and dashed lines indicate paths that will never be taken.

Below we give some examples of simple opaque constructs. These are easy to construct for the obfuscator and equally easy to crack for the deobfuscator. Section 8 provides examples of opaque constructs with much higher resilience.

6.1.1 Trivial and Weak Opaque Constructs

An opaque construct is trivial if a deobfuscator can crack it (i.e., deduce its value) by a static local analysis. An analysis is local if it is restricted to a single basic block of a

control flow graph. FIGs. 10a and 10b provide examples of (a) trivial opaque constructs and (b) weak opaque constructs.

We also consider an opaque variable to be
5 trivial if it is computed from calls to library functions with simple, well-understood semantics. For a language like the Java™, language which requires all implementations to support a standard set of library classes, such opaque variables are
10 easy to construct. A simple example is `int vs[1,5] = random(1,5)`, in which `random(a, b)` is a library function that returns an integer in the range `a . . . b`. Unfortunately, such opaque variables are equally easy to deobfuscate. All that is required
15 is for the deobfuscator-designer to tabulate the semantics of all simple library functions, and then pattern-match on the function calls in the obfuscated code.

An opaque construct is weak if a deobfuscator
20 can crack it by a static global analysis. An analysis is global if it is restricted to a single control flow graph.

6.2 Computation Transformations

25 Computation Transformations fall into three categories: hide the real control-flow behind irrelevant statements that do not contribute to the actual computations, introduce code sequences at the object code level for which there exist no
30 corresponding high-level language constructs, or

remove real control-flow abstractions or introduce spurious ones.

6.2.1 Insert Dead or Irrelevant Code

5 The u_2 and u_3 metrics suggest that there is a strong correlation between the perceived complexity of a piece of code and the number of predicates it contains. Using opaque predicates, we can devise transformations that introduce new
10 predicates in a program.

 Consider the basic block $S = S_1 \dots S_n$ in FIG. 11. In FIG. 11a, we insert an opaque predicate P^T into S , essentially splitting it in half. The P^T predicate is irrelevant code, because
15 it will always evaluate to True. In FIG. 11b, we again break S into two halves, and then proceed to create two different obfuscated versions S^a and S^b of the second half. S^a and S^b will be created by applying different sets of obfuscating
20 transformations to the second half of S . Hence, it will not be directly obvious to a reverse engineer that S^a and S^b in fact perform the same function. We use a predicate P^2 to select between S^a and S^b at runtime.

25 FIG. 11c is similar to FIG. 11b, but this time we introduce a bug into S^b . The P^T predicate always selects the correct version of the code, S^a .

6.2.2 Extend Loop Conditions

FIG. 12 shows how we can obfuscate a loop by making the termination condition more complex. The basic idea is to extend the loop condition with a P^T or P^F predicate that will not affect the number
5 of times the loop will execute. The predicate we have added in FIG. 12d, for example, will always evaluate to True because $x^2(x+1)^2=0 \pmod{4}$.

6.2.3 Convert a Reducible to a Non-Reducible Flow 10 Graph

Often, a programming language is compiled to a native or virtual machine code, which is more expressive than the language itself. When this is the case, it allows us to devise language-breaking
15 transformations. A transformation is language-breaking if it introduces virtual machine (or native code) instruction sequences that have no direct correspondence with any source language construct. When faced with such instruction
20 sequences a deobfuscator will either have to try to synthesize an equivalent (but convoluted) source language program or give up altogether.

For example, the Java™ bytecode has a goto instruction, but the Java™ language has no
25 corresponding goto statement. This means that the Java™ bytecode can express arbitrary control flow, whereas the Java™ language can only (easily) express structured control flow. Technically, we say that the control flow graphs produced from
30 Java™ programs will always be reducible, but the

Java™ bytecode can express non-reducible flow graphs.

Since expressing non-reducible flow graphs becomes very awkward in languages without gotos,
5 we construct a transformation that converts a reducible flow graph to a non-reducible one. This can be done by turning a structured loop into a loop with multiple headers. For example, in FIG. 13a, we add an opaque predicate P^F to a while
10 loop, to make it appear that there is a jump into the middle of the loop. In fact, this branch will never be taken.

A Java™ decompiler would have to turn a non-reducible flow graph into one which either
15 duplicates code or which contains extraneous Boolean variables. Alternatively, a deobfuscator could guess that all non-reducible flow graphs have been produced by an obfuscator, and simply remove the opaque predicate. To counter this we
20 can sometimes use the alternative transformation shown in FIG 13b. If a deobfuscator blindly removes P^F , the resulting code will be incorrect.

In particular, FIGs. 13a and 13b illustrate a transformation for transforming a Reducible flow graph to a Non-Reducible Flow graph. In FIG. 13a,
25 we split the loop body S_2 into two parts (S_2^a and S_2^b), and insert a bogus jump to the beginning of S_2^b . In FIG. 13b, we also break S_1 into two parts, S_1^a and S_1^b . S_1^b is moved into the loop and an opaque
30 predicate P^T ensures that S_1^b is always executed

before the loop body. A second predicate Q^F ensures that S_1^b is only executed once.

6.2.4 Remove Library Calls and Programming Idioms

5 Most programs written in Java rely heavily on calls to the standard libraries. Because the semantics of the library functions are well known, such calls can provide useful clues to a reverse engineer. The problem is exacerbated by the fact
10 that references to Java library classes are always by name, and these names cannot be obfuscated.

 In many cases the obfuscator will be able to counter this by simply providing its own versions of the standard libraries. For example, calls to
15 the Java Dictionary class (which uses a hash table implementation) could be turned into calls to a class with identical behavior, but implemented as, for example, a red-black tree. The cost of this transformation is not so much in execution time,
20 but in the size of the program.

 A similar problem occurs with clichés (or patterns), common programming idioms that occur frequently in many applications. An experienced reverse engineer will search for such patterns to
25 jump-start his understanding of an unfamiliar program. As an example, consider linked lists in Java™. The Java™ library has no standard class that provides common list operations such as insert, delete, and enumerate. Instead, most Java™
30 programmers will construct lists of objects in an

ad hoc fashion by linking them together on a next field. Iterating through such lists is a very common pattern in Java™ programs. Techniques invented in the field of automatic program
5 recognition (see Linda Mary Wills. Automated program recognition: a feasibility demonstration. Artificial Intelligence, 45(1--2):113--172, 1990, incorporated herein by reference) can be used to identify common patterns and replace them with
10 less obvious ones. In the linked list case, for example, we might represent the standard list data structure with a less common one, such as cursors into an array of elements.

15 6.2.5 Table Interpretation

One of the most effective (and expensive) transformations is table interpretation. The idea is to convert a section of code (Java bytecode in this example) into a different virtual machine
20 code. This new code is then executed by a virtual machine interpreter included with the obfuscated application. Obviously, a particular application can contain several interpreters, each accepting a different language and executing a different
25 section of the obfuscated application.

Because there is usually an order of magnitude slow down for each level of interpretation, this transformation should be reserved for sections of code that make up a small

part of the total runtime or which need a very high level of protection.

6.2.6 Add Redundant Operands

5 Once we have constructed some opaque variables we can use algebraic laws to add redundant operands to arithmetic expressions. This will increase the u_1 metric. Obviously, this technique works best with integer expressions
 10 where numerical accuracy is not an issue. In the obfuscated statement (1') below we make use of an opaque variable P whose value is 1. In statement (2') we construct an opaque subexpression P/Q whose value is 2. Obviously, we can let P and Q
 15 take on different values during the execution of the program, as long as their quotient is 2 whenever statement (2') is reached.

(1) $X=X+V;$ $\stackrel{T}{=}>$ (1') $X=X+V \cdot P^{-1};$
 20 (2) $Z=L+1;$ (2') $Z=L+(P^{-2Q}/Q^{P/2})/2.$

6.2.7 Parallelize Code

Automatic parallelization is an important compiler optimization used to increase the
 25 performance of applications running on multi-processor machines. Our reasons for wanting to parallelize a program, of course, are different. We want to increase parallelism not to increase performance, but to obscure the actual

flow of control. There are two possible operations available to us:

1. We can create dummy processes that perform no useful task, and
2. We can split a sequential section of the application code into multiple sections executing in parallel.

10

If the application is running on a single-processor machine, we can expect these transformations to have a significant execution time penalty. This may be acceptable in many situations, because the resilience of these transformations is high: static analysis of parallel programs is very difficult, because the number of possible execution paths through a program grows exponentially with the number of executing processes. Parallelization also yields high levels of potency: a reverse engineer will find a parallel program much more difficult to understand than a sequential one.

As shown in FIG. 14, a section of code can be easily parallelized if it contains no data dependencies. For example, if S_1 and S_2 are two data-independent statements they can be run in parallel. In a programming language like the Java™ language that has no explicit parallel

constructs, programs can be parallelized using calls to thread (lightweight process) libraries.

As shown in FIG. 15, a section of code that contains data dependencies can be split into
5 concurrent threads by inserting appropriate synchronization primitives, such as await and advance (see Michael Wolfe. High Performance Compilers For Parallel Computing. Addison-Wesley, 1996. ISBN 0-8053-2730-4, incorporated herein by
10 reference). Such a program will essentially be running sequentially, but the flow of control will be shifting from one thread to the next.

6.3 Aggregation Transformations

15 Programmers overcome the inherent complexity of programming by introducing abstractions. There is abstraction on many levels of a program, but the procedural abstraction is the most important one. For this reason, obscuring procedure and
20 method calls can be important to the obfuscator. Below, we will consider several ways in which methods and method invocations can be obscured: inlining, outlining, interleaving, and cloning. The basic idea behind all of these is the same:
25 (1) code that the programmer aggregated into a method (presumably because it logically belonged together) should be broken up and scattered over the program and (2) code that seems not to belong together should be aggregated into one method.

6.3.1 Inline and Outline Methods

Inlining is, of course, a important compiler optimization. It is also an extremely useful
5 obfuscation transformation, because it removes procedural abstractions from the program. Inlining is a highly resilient transformation (it is essentially one-way), because once a procedure call has been replaced with the body of the called
10 procedure and the procedure itself has been removed, there is no trace of the abstraction left in the code. FIG. 16 shows how procedures P and Q are inlined at their call-sites, and then removed from the code.

15 Outlining (turning a sequence of statements into a subroutine) is a very useful companion transformation to inlining. We create a bogus procedural abstraction by extracting the beginning of Q's code and the end of P's code into a new
20 procedure R.

In object-oriented languages such as the Java™ language, inlining may, in fact, not always be a fully one-way transformation. Consider a method invocation `m.P()`. The actual procedure
25 called will depend on the run-time type of `m`. In cases when more than one method can be invoked at a particular call site, we inline all possible methods (see Jeffrey Dean. Whole-Program Optimization of Object-Oriented Languages. PhD
30 thesis, University of Washington, 1996,

incorporated herein by reference) and select the appropriate code by branching on the type of m). Hence, even after inlining and removal of methods, the obfuscated code may still contain some traces of the original abstractions. For example, FIG. 17 illustrates inlining method calls. Unless we can statically determine the type of m, all possible methods to which m.P() could be bound must be inlined at the call site.

10

6.3.2 Interleave Methods

The detection of interleaved code is an important and difficult reverse engineering task.

FIG. 18 shows how we can interleave two methods declared in the same class. The idea is to merge the bodies and parameter lists of the methods and add an extra parameter (or global variable) to discriminate between calls to the individual methods. Ideally, the methods should be similar in nature to allow merging of common code and parameters. This is the case in FIG. 18, in which the first parameter of M1 and M2 have the same type.

15

20

25 6.3.3 Clone Methods

When trying to understand the purpose of a subroutine a reverse engineer will of course examine its signature and body. However, equally important to understanding the behavior of the routine are the different environments in which it

30

is being called. We can make this process more difficult by obfuscating a method's call sites to make it appear that different routines are being called, when, in fact, this is not the case.

5 FIG. 19 shows how we can create several different versions of a method by applying different sets of obfuscating transformations to the original code. We use method dispatch to select between the different versions at runtime.

10 Method cloning is similar to the predicate insertion transformations in FIG. 11, except that here we are using method dispatch rather than opaque predicates to select between different versions of the code.

15

6.3.4 Loop Transformations

A large number of loop transformations have been designed with the intent to improve the performance of (in particular) numerical
20 applications. See Bacon [2] for a comprehensive survey. Some of these transformations are useful to us, because they also increase the complexity metrics, which are discussed above with respect to FIG. 7. Loop Blocking, as shown in FIG. 20a, is
25 used to improve the cache behavior of a loop by breaking up the iteration space so that the inner loop fits in the cache. Loop unrolling, as shown in FIG. 20b, replicates the body of a loop one or more times. If the loop bounds are known at
30 compile time the loop can be unrolled in its

entirety. Loop fission, as shown in FIG. 20c, turns a loop with a compound body into several loops with the same iteration space.

5 All three transformations increase the u_1 and u_2 metrics, because they increase the source application's total code size and number of conditions. The loop blocking transformation also introduces extra nesting, and hence also increases the u_3 metric.

10 Applied in isolation, the resilience of these transformations is quite low. It does not require much static analysis for a deobfuscator to reroll an unrolled loop. However, when the transformations are combined, the resilience rises
15 dramatically. For example, given the simple loop in FIG. 20b, we could first apply unrolling, then fission, and finally blocking. Returning the resulting loop to its original form would require a fair amount of analysis for the deobfuscator.

20

6.4 Ordering Transformations

Programmers tend to organize their source code to maximize its locality. The idea is that a program is easier to read and understand if two
25 items that are logically related are also physically close in the source text. This kind of locality works on every level of the source: for example, there is locality among terms within expressions, statements within basic blocks, basic
30 blocks within methods, methods within classes, and

classes within files. All kinds of spatial locality can provide useful clues to a reverse engineer. Therefore, whenever possible, we randomize the placement of any item in the source application. For some types of items (methods within classes, for example) this is trivial. In other cases (such as statements within basic blocks) a data dependency analysis (see David F. Bacon, Susan L. Graham, and Oliver J. Sharp. 10 Compiler transformations for high-performance computing. ACM Computing Surveys, 26(4):345--420, December 1994. <http://www.acm.org/pubs/toc/Abstracts/0360-0300/197406.html>. and Michael Wolfe. High Performance 15 Compilers For Parallel Computing. Addison-Wesley, 1996. ISBN 0-8053-2730-4, incorporated herein by reference) is performed to determine which reorderings are technically valid.

These transformations have low potency (they 20 do not add much obscurity to the program), but their resilience is high, in many cases one-way. For example, when the placement of statements within a basic block has been randomized, there will be no traces of the original order left in 25 the resulting code.

Ordering transformations can be particularly useful companions to the "Inline-Outline" transformation of Section 6.3.1. The potency of that transformation can be enhanced by (1) 30 inlining several procedure calls in a procedure P,

(2) randomizing the order of the statements in P,
and (3) outlining contiguous sections of P's
statements. This way, unrelated statements that
were previously part of several different
5 procedures are brought together into bogus
procedural abstractions.

In certain cases it is also possible to
reorder loops, for example by running them
backwards. Such loop reversal transformations are
10 common in high-performance compilers (David F.
Bacon, Susan L. Graham, and Oliver J. Sharp.
Compiler transformations for high-performance
computing. ACM Computing Surveys, 26(4):345--420,
December 1994. [http://](http://www.acm.org/pubs/toc/Abstracts/0360-0300/197406.html)
15 [www.acm.org/pubs/toc/Abstracts/0360-0300/](http://www.acm.org/pubs/toc/Abstracts/0360-0300/197406.html)
[197406.html](http://www.acm.org/pubs/toc/Abstracts/0360-0300/197406.html)).

7 Data Transformations

In this section we will discuss
20 transformations that obscure the data structures
used in the source application. As indicated in
FIG. 2e, we classify these transformations as
affecting the storage, encoding, aggregation, or
ordering of the data.

25

7.1 Storage and Encoding Transformations

In many cases there is a "natural" way to
store a particular data item in a program. For
example, to iterate through the elements of an
30 array we probably would choose to allocate a local

integer variable of the appropriate size as the iteration variable. Other variable types might be possible, but they would be less natural and probably less efficient.

5 Furthermore, there is also often a "natural" interpretation of the bit-patterns that a particular variable can hold which is based on the type of the variable. For example, we would normally assume that a 16-bit integer variable
10 storing the bit-pattern 0000000000001100 would represent the integer value 12. Of course, these are mere conventions and other interpretations are possible.

 Obfuscating storage transformations attempt
15 to choose unnatural storage classes for dynamic as well as static data. Similarly, encoding transformations attempt to choose unnatural encodings for common data types. Storage and encoding transformations often go hand-in-hand,
20 but they can sometimes be used in isolation.

7.1.1 Change Encoding

 As a simple example of an encoding transformation we will replace an integer variable
25 i by $i_0 = c_1 * i + c_2$, where c_1 and c_2 are constants. For efficiency, we could choose c_1 to be a power of two. In the example below, we let $c_1 = 8$ and $c_2 = 3$:

```

{                               =T=>                               {
    int i=1;                      int i=11;
    while (i < 1000)              while (i < 8003)
        . . . A[i] . . . ;        . . A[(i-3)/8] . . . ;
5      i++;                      i+=8;
    }                             }

```

Obviously, overflow (and, in case of floating point variables, accuracy) issues need to be addressed. We could either determine that because of the range of the variable (the range can be determined using static analysis techniques or by querying the user) in question no overflow will occur, or we could change to a larger variable type.

There will be a trade-off between resilience and potency on one hand, and cost on the other. A simple encoding function such as $i_0 = c_1 + i + c_2$ in the example above, will add little extra execution time but can be deobfuscated using common compiler analysis techniques (Michael Wolfe. High Performance Compilers For Parallel Computing. Addison-Wesley, 1996. ISBN 0-8053-2730-4. and David F. Bacon, Susan L. Graham, and Oliver J. Sharp. Compiler transformations for high-performance computing. ACM Computing Surveys, 26(4):345--420, December 1994. <http://www.acm.org/pubs/toc/Abstracts/0360-0300/197406.html>).

7.1.2 Promote Variables

There are a number of simple storage transformations that promote variables from a specialized storage class to a more general class. Their potency and resilience are generally low, but used in conjunction with other transformations they can be quite effective. For example, in Java, an integer variable can be promoted to an integer object. The same is true of the other scalar types which all have corresponding "packaged" classes. Because Java™ supports garbage collection, the objects will be automatically removed when they are no longer referenced. Here is an example:

```

15
{
    {
int I=1;                int i = new int(1);
while (i < 9)  =T=> while (i.value < 9)
    ...A[i]...;        ...A[i.value]...;
20    i++;              i.value++;
    }
    }

```

It is also possible to change the lifetime of a variable. The simplest such transform turns a local variable into a global one which is then shared between independent procedure invocations. For example, if procedures P and Q both reference a local integer variable, and P and Q cannot both be active at the same time (unless the program contains threads, this can be determining by

examining the static call graph) then the variable can be made global and shared between them:

```

void P() {          int C;
5  int i; ...I...    void P(){
    }                ...C...
                    }
void Q(){           =T=> while (i.value<9)
int k;...k...       ...C...
10 }                }

```

This transformation increases the u_s metric, because the number of global data structures referenced by P and Q is increased.

15

7.1.3 Split Variables

Boolean variables and other variables of restricted range can be split into two or more variables. We will write a variable V split into k
20 variables p_1, \dots, p_k as $V = [p_1, \dots, p_k]$. Typically, the potency of this transformation will grow with k. Unfortunately, so will the cost of the transformation, so we usually restrict k to 2 or 3.

25 To allow a variable V of type T to be split into two variables p and q of type U requires us to provide three pieces of information: (1) a function $f(p; q)$ that maps the values of p and q into the corresponding value of V, (2) a function
30 $g(V)$ that maps the value of V into the

corresponding values of p and q , and (3) new operations (corresponding to the primitive operations on values of type T) cast in terms of operations on p and q . In the remainder of this section we will assume that V is of type Boolean, and p and q are small integer variables.

FIG. 21a shows a possible choice of representation for split Boolean variables. The table indicates that if V has been split into p and q , and if, at some point in the program, $p = q = 0$ or $p = q = 1$, then that corresponds to V being False. Similarly, $p = 0, q = 1$ or $p = 1, q = 0$ corresponds to True.

Given this new representation, we have to devise substitutions for various built-in Boolean operations (e.g., &, or). One approach is to provide a run-time lookup table for each operator. Tables for "AND" and "OR" are shown in FIGs. 21c and 21d, respectively. Given two Boolean variables $V_1 = [p, q]$ and $V_2 = [r, s]$, $V_1 \& V_2$ is computed as $\text{AND}[2p + q, 2r + s]$.

In FIG. 21e, we show the result of splitting three Boolean variables $A=[a1,a2]$, $B=[b1,b2]$, and $C=[c1,c2]$. An interesting aspect of our chosen representation is that there are several possible ways to compute the same Boolean expression. Statements (3') and (4') in FIG. 21e, for example, look different, although they both assign False to a variable. Similarly, while statements (5') and

(6') are completely different, they both compute A & B.

The potency, resilience, and cost of this transformation all grow with the number of variables into which the original variable is split. The resilience can be further enhanced by selecting the encoding at run-time. In other words, the run-time look-up tables of FIGs. 21b through 21d are not constructed at compile-time (which would make them susceptible to static analyses) but by algorithms included in the obfuscated application. This, of course, would prevent us from using in-line code to compute primitive operations, as done in statement (6') in FIG. 21e.

7.1.4 Convert Static to Procedural Data

Static data, particularly character strings, contain much useful pragmatic information to a reverse engineer. A technique for obfuscating a static string is to convert it into a program that produces the string. The program -- which could be a DFA or a Trie traversal -- could possibly produce other strings as well.

As an example, consider a function G of FIG. 22, which is constructed to obfuscate the strings 'AAA', 'BAAAA', and 'CCB'. The values produced by G are G(1)='AAA', G(2)='BAAAA', G(3)=G(5)='CCB', and G(4)='XCB' (which is not

actually used in the program). For other argument values, G may or may not terminate.

Aggregating the computation of all static string data into just one function is, of course,
5 highly undesirable. Much higher potency and resilience is achieved if the G-function was broken up into smaller components that were embedded into the ``normal'' control flow of the source program.

10 It is interesting to note that we can combine this technique with the table interpretation transformation of Section 6.2.5. The intent of that obfuscation is to convert a section of Java bytecode into code for another virtual machine.
15 The new code will typically be stored as static string data in the obfuscated program. For even higher levels of potency and resilience, however, the strings could be converted to programs that produce them, as discussed above.

20

7.2 Aggregation Transformations

In contrast to imperative and functional languages, object-oriented languages are more data-oriented than control-oriented. In other
25 words, in an object-oriented program, the control is organized around the data structures, rather than the other way around. This means that an important part of reverse-engineering an object-oriented application is trying to restore
30 the program's data structures. Conversely, it is

important for an obfuscator to try to hide these data structures.

In most object-oriented languages, there are just two ways to aggregate data: in arrays and in objects. In the next three sections we will examine ways in which these data structures can be obfuscated.

7.2.1 Merge Scalar Variables

Two or more scalar variables $V_1 \dots V_k$ can be merged into one variable V_M , provided the combined ranges of $V_1 \dots V_k$ will fit within the precision of V_M . For example, two 32-bit integer variables could be merged into one 64-bit variable. Arithmetic on the individual variables would be transformed into arithmetic on V_M . As a simple example, consider merging two 32-bit integer variables X and Y into a 64-bit variable Z . Using the merging formula,

$$Z(X, Y) = 2^{32} * Y + X$$

we get the arithmetic identities in FIG. 23a. Some simple examples are given in FIG. 23b.

In particular, FIG. 23 shows merging two 32-bit variables X and Y into one 64-bit variable Z . Y occupies the top 32 bits of Z , X the bottom 32 bits. If the actual range of either X or Y can be deduced from the program, less intuitive merges could be used. FIG. 23a gives rules for addition

and multiplication with X and Y. FIG. 23b shows some simple examples. The example could be further obfuscated, for example by merging (2') and (3') into $Z += 47244640261$.

5 The resilience of variable merging is quite low. A deobfuscator only needs to examine the set of arithmetic operations being applied to a particular variable in order to guess that it actually consists of two merged variables. We can
 10 increase the resilience by introducing bogus operations that could not correspond to any reasonable operations on the individual variables. In the example in FIG. 23b, we could insert operations that appear to merge Z's two halves,
 15 for example, by rotation: if (P^F) $Z = \text{rotate}(Z, 5)$.

A variant of this transformation is to merge $V_1 \dots V_k$ into an array

20 $V_A = \begin{matrix} 1 & \dots & k \\ V_1 & \dots & V_k \end{matrix}$

of the appropriate type. If $V_1 \dots V_k$ are object reference variables, for example, then the element type of V_A can be any class that is higher in the
 25 inheritance hierarchy than any of the types of $V_1 \dots V_k$.

7.2.2 Restructure Arrays

A number of transformations can be devised
 30 for obscuring operations performed on arrays: for

example, we can split an array into several sub-arrays, merge two or more arrays into one array, fold an array (increasing the number of dimensions), or flatten an array (decreasing the
5 number of dimensions).

FIG. 24 shows some examples of array restructuring. In statements (1-2) an array A is split up into two sub-arrays A1 and A2. A1 holds the elements of A that have even indices, and A2
10 holds the elements with odd indices.

Statements (3-4) of FIG. 24 show how two integer arrays B and C can be interleaved into a resulting array BC. The elements from B and C are evenly spread over the resulting array.

15 Statements (6-7) demonstrate how a one-dimensional array D can be folded into a two-dimensional array D1. Statements (8-9), finally, demonstrate the reverse transformation: a two-dimensional array E is flattened into a
20 one-dimensional array E1.

Array splitting and folding increase the u_6 data complexity metric. Array merging and flattening, on the other hand, seem to decrease this measure. While this may seem to indicate that
25 these transformations have only marginal or even negative potency, this, in fact, is deceptive. The problem is that the complexity metrics of FIG. 7 fail to capture an important aspect of some data structure transformations: they introduce
30 structure where there was originally none or they

remove structure from the original program. This can greatly increase the obscurity of the program. For example, a programmer who declares a two-dimensional array does so for a purpose: the chosen structure somehow maps cleanly to the data that is being manipulated. If that array is folded into a one-dimensional structure, a reverse engineer will have been deprived of much valuable pragmatic information.

10

7.2.3 Modify Inheritance Relations

In current object-oriented language such as the Java™ language, the main modularization and abstraction concept is the class. Classes are essentially abstract data types that encapsulate data (instance variables) and control (methods). We write a class as $C = (V, M)$, where V is the set of C 's instance variables and M its methods.

15

In contrast to the traditional notion of abstract data types, two classes C_1 and C_2 can be composed by aggregation (C_2 has an instance variable of type C_1) as well as by inheritance (C_2 extends C_1 by adding new methods and instance variables). We write inheritance as $C_2 = C_1 \cup C'_2$. C_2 is said to inherit from C_1 , its super- or parent class. The \cup operator is the function that combines the parent class with the new properties defined in C'_2 . The exact semantics of \cup depends on the particular programming language. In languages such as Java, \cup is usually interpreted as union

20

25

30

when applied to the instance variables and as overriding when applied to methods.

According to metric u_7 , the complexity of a class C_1 grows with its depth (distance from the root) in the inheritance hierarchy and the number of its direct descendants. For example, there are two basic ways in which we can increase this complexity: we can split up (factor) a class as shown in FIG. 25a or insert a new, bogus, class as shown in FIG. 25b.

A problem with class factoring is its low resilience; there is nothing stopping a deobfuscator from simply merging the factored classes. To prevent this, factoring and insertion are normally combined as shown in FIG. 25d. Another way of increasing the resilience of these types of transformations is to make sure that new objects are created of all introduced classes.

FIG. 25c shows a variant of class insertion, called false refactoring. Refactoring is a (sometimes automatic) technique for restructuring object-oriented programs whose structure has deteriorated (see William F. Opdyke and Ralph E. Johnson. Creating abstract superclasses by refactoring. In Stan C. Kwasny and John F. Buck, editors, Proceedings of the 21st Annual Conference on Computer Science, pages 66--73, New York, NY, USA, February 1993. ACM Press.
[ftp://st.cs.uiuc.edu/pub/papers/refactoring/refact](ftp://st.cs.uiuc.edu/pub/papers/refactoring/refactoring-superclasses.ps)
oring-superclasses.ps, incorporated herein by

reference). Refactoring is a two-step process. First, it is detected that two, apparently independent classes, in fact implement similar behavior. Secondly, features common to both

5 classes are moved into a new (possibly abstract) parent class. False refactoring is a similar operation, only it is performed on two classes C_1 and C_2 that have no common behavior. If both classes have instance variables of the

10 same type, these can be moved into the new parent class C_3 . C_3 's methods can be buggy versions of some of the methods from C_1 and C_2 .

7.3 Ordering Transformations

15 In Section 6.4 we showed that (when possible) randomizing the order in which computations are performed is a useful obfuscation. Similarly, it is useful to randomize the order of declarations in the source application.

20 Particularly, we randomize the order of methods and instance variables within classes and formal parameters within methods. In the latter case, the corresponding actuals will of course have to be reordered as well. The potency of these

25 transformations is low and the resilience is one-way.

In many cases it will also be possible to reorder the elements within an array. Simply put, we provide an opaque encoding function $f(i)$ which

maps the i :th element in the original array into its new position of the reordered array:

```

    {
5  int i=1, A[1000];
    while (i < 1000)    =T=>    while (i < 1000)
        ...A[i]...;          ...A[f(i)]...;
        i++;                  i++;
    }                        }
10

```

8 Opaque Values and Predicates

As we have seen, opaque predicates are the major building block in the design of transformations that obfuscate control flow. In fact, the quality of most control transformations is directly dependent on the quality of such predicates.

In Section 6.1 we gave examples of simple opaque predicates with trivial and weak resilience. This means that the opaque predicates can be broken (an automatic deobfuscator could determine their value) using local or global static analysis. Obviously, we generally require a much higher resistance to attack. Ideally, we would like to be able to construct opaque predicates that require worst case exponential time (in the size of the program) to break but only polynomial time to construct. In this section we will present two such techniques. The first one

is based on aliasing and the second is based on lightweight processes.

8.1 Opaque Constructs Using Objects and Aliases

5 Inter-procedural static analysis is significantly complicated whenever there is a possibility of aliasing. In fact, precise, flow-sensitive alias analysis is undecidable in languages with dynamic allocation, loops, and
10 if-statements.

 In this section we will exploit the difficulty of alias analysis to construct opaque predicates that are cheap and resilient to automatic deobfuscation attacks.

15

8.2 Opaque Constructs Using Threads

 Parallel programs are more difficult to analyze statically than their sequential counterparts. The reason is their interleaving
20 semantics: n statements in a parallel region PAR S_1, S_2, \dots, S_n , ENDPAR can be executed in $n!$ different ways. In spite of this, some static analyses over parallel programs can be performed in polynomial time [18], while others
25 require all $n!$ interleavings to be considered.

 In Java, parallel regions are constructed using lightweight processes known as threads. Java threads have (from our point of view) two very useful properties: (1) their scheduling policy is
30 not specified strictly by the language

specification and will hence depend on the implementation, and (2) the actual scheduling of a thread will depend on asynchronous events, such as generated by user interaction, and network
5 traffic. Combined with the inherent interleaving semantics of parallel regions, this means that threads are very difficult to analyze statically.

We will use these observations to create opaque predicates (see FIG. 32) that will require
10 worst-case exponential time to break. The basic idea is very similar to the one used in Section 8.2: a global data structure V is created and occasionally updated, but kept in a state such that opaque queries can be made. The difference is
15 that V is updated by concurrently executing threads.

Obviously, V can be a dynamic data structure such as the one created in FIG. 26. The threads would randomly move the global pointers g and h
20 around in their respective components, by asynchronously executing calls to move and insert. This has the advantage of combining data races with interleaving and aliasing effects, for very high degrees of resilience.

25 In FIG. 27, we illustrate these ideas with a much simpler example where V is a pair of global integer variables X and Y . It is based on the well-known fact from elementary number theory that, for any integers x and y , $7y^2 - 1$ does not
30 equal x^2 .

9 Deobfuscation and Preventive Transformations

Many of our obfuscating transformations (particularly the control transformations of Section 6.2) can be said to embed a bogus program within a real program. In other words, an obfuscated application really consists of two programs merged into one: a real program which performs a useful task and a bogus program which computes useless information. The sole purpose of the bogus program is to confuse potential reverse engineers by hiding the real program behind irrelevant code.

The opaque predicate is the main device the obfuscator has at its disposal to prevent the bogus inner program from being easily identified and removed. For example, in FIG. 28a, an obfuscator embeds bogus code protected by opaque predicates within three statements of a real program. A deobfuscator's task is to examine the obfuscated application and automatically identify and remove the inner bogus program. To accomplish this, the deobfuscator must first identify and then evaluate opaque constructs. This process is illustrated in FIGs. 28b through 28d.

FIG. 29 shows the anatomy of a semi-automatic deobfuscation tool. It incorporates a number of techniques that are well known in the reverse engineering community. In the remainder of this section we will briefly review some of these

techniques and discuss various counter-measures (so called preventive transformations) that an obfuscator can employ to make deobfuscation more difficult.

5

9.1 Preventive Transformations

Preventive transformations, which are discussed above with respect to FIG. 2g, are quite different in flavor from control or data transformations. In contrast to these, their main goal is not to obscure the program to a human reader. Rather, they are designed to make known automatic deobfuscation techniques more difficult (inherent preventive transformations), or to explore known problems in current deobfuscators or decompilers (targeted preventive transformations).

9.1.1 Inherent Preventive Transformations

Inherent preventive transformations will generally have low potency and high resilience. Most importantly, they will have the ability to boost the resilience of other transformations. As an example, assume that we have reordered a for-loop to run backwards, as suggested in section 6.4. We were able to apply this transformation only because we could determine that the loop had no loop-carried data dependencies. Naturally, there is nothing stopping a deobfuscator from performing the same analysis and then returning the loop to forward execution. To prevent this, we

30

can add a bogus data dependency to the reversed loop:

```

    {
5   for(i=1;i<=10;i++)  =T=>    int B[50];
        A[i]=i                for(i=10;i<=1;i--)
    }                          A[i]=i;
                                B[i]+=B[i*i/2]
                                }
10

```

The resilience this inherent preventive transformation adds to the loop reordering transformation depends on the complexity of the bogus dependency and the state-of-the-art in
15 dependency analysis [36].

9.1.2 Targeted Preventive Transformations

As an example of a targeted preventive transformation, consider the HoseMocha program
20 (Mark D. LaDue. HoseMocha. <http://www.xynyx.demon.nl/java/HoseMocha.java>, January 1997). It was designed specifically to explore a weakness in the Mocha (Hans Peter Van Vliet. Mocha --- The Java decompiler. <http://web.inter.nl.net/users/H.P.van.Vliet/mocha.html>, January 1996) decompiler.
25 HoseMocha inserts extra instructions after every return-statement in every method in the source program. This transformation has no effect on the behavior of the application, but it is enough to
30 make Mocha crash.

9.2 Identifying and Evaluating Opaque Constructs

The most difficult part of deobfuscation is identifying and evaluating opaque constructs. Note that identification and evaluation are distinct activities. An opaque construct can be local (contained within a single basic block), global (contained within a single procedure), or inter-procedural (distributed throughout the entire program). For example, if $(x * x == (7^F * y * y - 1))$ is a local opaque predicate, whereas $R = X * X; \dots; S = 7 * y * y - 1; \dots; \text{if } (R == S^F) \dots$ is global. If the computation of R and S were performed in different procedures, the construct would be inter-procedural. Obviously, identification of a local opaque predicate is easier than identification of an inter-procedural one.

9.3 Identification by Pattern Matching

A deobfuscator can use knowledge of the strategies employed by known obfuscators to identify opaque predicates. A designer of a deobfuscator could examine an obfuscator (either by decompiling it or simply by examining the obfuscated code it generates) and construct pattern-matching rules that can identify commonly used opaque predicates. This method will work best for simple local predicates, such as $x * x == (7 * y * y - 1)$ or $\text{random}(1^F, 5) < 0$

To thwart attempts at pattern matching, the obfuscator should avoid using canned opaque constructs. It is also important to choose opaque constructs that are syntactically similar to the
5 constructs used in the real application.

9.4 Identification by Program Slicing

A programmer will generally find the obfuscated version of a program more difficult to
10 understand and reverse engineer than the original one. The main reasons are that in the obfuscated program (a) live "real" code will be interspersed with dead bogus code, and (b) logically related pieces of code will have been broken up and
15 dispersed over the program. Program slicing tools can be used by a reverse engineer to counter these obfuscations. Such tools can interactively aid the engineer to decompose a program into manageable chunks called slices. A slice of a program P with
20 respect to a point p and a variable v consists of all the statements of P that could have contributed to v's value at p. Hence, a program slicer would be able to extract from the obfuscated program the statements of the algorithm
25 that computes an opaque variable v, even if the obfuscator has dispersed these statements over the entire program.

There are several strategies available to an obfuscator to make slicing a less useful
30 identification tool: Add parameter aliases A

parameter alias is two formal parameters (or a formal parameter and a global variable) that refer to the same memory location. The cost of precise inter-procedural slicing grows with the number of potential aliases in a program, which in turn grows exponentially with the number of formal parameters. Hence, if the obfuscator adds aliased dummy parameters to a program it will either substantially slow down the slicer (if precise slices are required), or force the slicer to produce imprecise slices (if fast slicing is required).

Add variable dependencies, as popular slicing tools such as Unravel (James R. Lyle, Dolorres R. Wallace, James R. Graham, Keith B. Gallagher, Joseph P. Poole, and David W Binkley. Unravel: A CASE tool to assist evaluation of high integrity software. Volume 1: Requirements and design. Technical Report NIS-20 TIR 5691, U.S. Department of Commerce, August 1995) work well for small slices, but will sometimes require excessive time to compute larger ones. For example, when working on a 4000 line C program, Unravel in some cases required over 30 minutes to compute a slice. To force this behavior, the obfuscator should attempt to increase slice sizes, by adding bogus variable dependencies. In the example below, we have increased the size of the slice computing

x by adding two statements which apparently contribute to x's value, but which, in fact, do not.

```

5  main()      {      =T=>      main() {
    int x=1;          int x=1;
    x = x * 3;        if (PF) x++;
    }                x = x + V0 ;
                    x = x * 3;
10                  }

```

9.5 Statistical Analysis

A deobfuscator can instrument an obfuscated program to analyze the outcome of all predicates.

15 We will call any deobfuscation method that examines the run-time characteristics of an obfuscated application in this way, Statistical Analysis. The deobfuscator would alert the reverse engineer to any predicate that always returns the same truth value over a large number of test runs, because they may turn out to be an opaque P^T (P^F) predicate. The deobfuscator could not blindly replace such predicates with True (False), because this would be too dangerous. Many applications

20 will contain ``real'' predicates that check for conditions that only happen under exceptional circumstances, and to the deobfuscator they will appear to behave identically to an opaque predicate. As an example, consider pif (Leap Year)

25

30

Statistical analysis can also be used for evaluation. When a potential opaque predicate (e.g., P^T) in a program M has been identified, we guess its value (True), and make a version M' of the obfuscated program where the opaque predicate has been replaced by the guessed value. We then run M and M' in parallel on the same input, and compare to see that they produce identical output. If the outputs are the same, we can conclude that the predicate was part of the bogus, not the real, application, as shown in FIG. 30.

We have to make sure that our chosen inputs adequately cover all paths in the program. Again, if the program contains paths that are rarely taken (if (Leap Year) . . .) this will be difficult. Furthermore, generating large numbers of correct input/output data is very difficult, particularly when internal structure of the application is unknown, or the input is entered (as is often the case with Java programs) through a complex graphical user interface.

To prevent identification by statistical analysis, the obfuscator may choose to favor transformations that insert $P^?$ predicates (such as the one shown in FIG. 11b) over those that insert P^T or P^F predicates.

Another possible counter-measure against statistical analysis is to design opaque predicates in such a way that several predicates have to be cracked at the same time. One way of

doing this is to let the opaque predicates have side-effects. In the example below the obfuscator has determined (through some sort of static flow analysis) that statements S_1 and S_2 must always
 5 execute the same number of times. The statements are obfuscated by introducing opaque predicates which are calls to functions Q_1 and Q_2 . Q_1 and Q_2 increment and decrement a global variable k :

```

10  {      =T=>      {
    S1;          int k=0;
    S2;          bool Q1 (x) {
    }             k+=231 ; return (PT1 )}
                  bool Q2 (x) {
15                  k-=231 ; return (PT2 )}
                  {
                    if (Q1 (j) T ) S1 ;
                        . . .
                    if (Q2 (k) T ) S2 ;
20                  }
  
```

If the deobfuscator tries to replace one (but not both) predicates with True, k will overflow. As a result, the deobfuscated program will
 25 terminate with an error condition.

9.6 Evaluation by Data-Flow Analysis

Deobfuscation is similar to many types of code optimization. Removing if (False) . . . is
 30 dead code elimination and moving identical code

from if-statement branches (e.g., S_1 and S_0^1 in FIG. 28) is code hoisting, both common code optimization techniques.

When an opaque construct has been identified
 5 we can attempt to evaluate it. In simple cases constant propagation using a reaching definition data-flow analysis can be sufficient: $x=5; . . . ; y=7; . . . ; \text{if } (x*x==(7*y*y-1))$

10 9.7 Evaluation by Theorem Proving

If data-flow analysis is not powerful enough to break the opaque predicate, a deobfuscator can attempt to use a theorem prover. Whether this is doable or not depends on the power of
 15 state-of-the-art theorem provers (which is difficult to ascertain) and the complexity of the theorem that needs to be proven. Certainly, theorems that can be proved by induction (such as $x^2(x+1)^2 = 0 \pmod{4}$), are well within reach of
 20 current theorem provers.

To make things more difficult, we can use theorems which are known to be difficult to prove, or for which no known proof exists. In the example below the deobfuscator will have to prove that the
 25 bogus loop always terminates in order to determine that S_2 is live code:

$$\left\{ \begin{array}{l} \\ S_1; \end{array} \right. \stackrel{T}{=} \Rightarrow \left\{ \begin{array}{l} \\ S_1; \end{array} \right.$$

```

S2;          n = random(1,232);
}            do
              n = ((n%2)!=0)?3*n+1:n/2
              while (n>1);
5           S2;
              }

```

This is known as the Collatz problem. A conjecture
 says that the loop will always terminate. Although
 10 there is no known proof of this conjecture, the
 code is known to terminate for all numbers up to
 7*10¹¹. Thus, this obfuscation is safe (the
 original and obfuscated code behave identically),
 but is difficult to deobfuscate.

15

9.8 Deobfuscation and Partial Evaluation

Deobfuscation also resembles partial
 evaluation. A partial evaluator splits a program
 into two parts: the static part which can be
 20 precomputed by the partial evaluator, and the
 dynamic part which is executed at runtime. The
 dynamic part would correspond to our original,
 unobfuscated, program. The static part would
 correspond to our bogus inner program, which, if
 25 it were identified, could be evaluated and removed
 at deobfuscation time.

Like all other static inter-procedural
 analysis methods, partial evaluation is sensitive
 to aliasing. Hence, the same preventive

transformations that were discussed in relation to slicing also applies to partial evaluation.

10 Obfuscation Algorithms

5 Given the obfuscator architecture of Section 3, the definition of obfuscation quality in Section 5, and the discussion of various obfuscating transformations in Section 6 through Section 9, we are now in a position to present
10 more detailed algorithms, in accordance with one embodiment of the present invention.

The top-level loop of an obfuscation tool can have this general structure:

```
15  WHILE NOT Done(A) DO
      S := SelectCode(A);
      T := SelectTransform(S);
      A := Apply(T ,S);
  END;
```

20

SelectCode returns the next source code object to be obfuscated. SelectTransform returns the transformation which should be used to obfuscate the particular source code object. Apply applies
25 the transformation to the source code object and updates the application accordingly. Done determines when the required level of obfuscation has been attained. The complexity of these functions will depend on the sophistication of the
30 obfuscation tool. At the simplistic end of the

scale, SelectCode and SelectTransform could simply return random source code object/transformations, and Done could terminate the loop when the size of the applica-

5 tion exceeds a certain limit. Normally, such behavior is insufficient.

Algorithm 1 gives a description of a code obfuscation tool with a much more sophisticated selection and termination behavior. In one
10 embodiment, the algorithm makes use of several data structures, which are constructed by Algorithms 5, 6, and 7:

15 P_s For each source code object S , $P_s(S)$ is the set of language constructs the programmer used in S . $P_s(S)$ is used to find appropriate obfuscating transformations for S .

20 A For each source code object S , $A(S) = \{T_1 \rightarrow V_1 ; \dots ; T_n \rightarrow V_n\}$ is a mapping from transformations T_i to values V_i , describing how appropriate it would be to apply T_i to S . The idea is
25 that certain transformations may be inappropriate for a particular source code object S , because they introduce new code which is ``unnatural'' to S . The new code would look out of place in
30 S and hence would be easy to spot for a

reverse engineer. The higher the appropriateness value V_i the better the code introduced by transformation T_i will fit in.

5

I For each source code object S , $I(S)$ is the obfuscation priority of S . $I(S)$ describes how important it is to obfuscate the contents of S . If S contains an important trade secret then $I(S)$ will be high, if it contains mainly ``bread-and-butter'' code $I(S)$ will be low.

10

15

R For each routine M , $R(M)$ is the execution time rank of M . $R(M) = 1$ if more time is spent executing M than any other routine.

20

The primary input to Algorithm 1 is an application A and a set of obfuscating transformations $\{ T_1 ; T_2 ; \dots \}$. The algorithm also requires information regarding each transformation, particularly three quality functions $T_{res}(S)$, $T_{pot}(S)$, and $T_{cost}(S)$ (similar to their namesakes in Section 5, but returning numerical values) and a function P_t :

25

30

$T_{res}(S)$ returns a measure of the resilience of transformation T when applied to source code

object S (i.e., how well T will withstand an attack from an automatic deobfuscator).

5 $T_{\text{pot}}(S)$ returns a measure of the potency of transformation T when applied to source code object S (i.e., how much more difficult S will be for a human to understand after having been obfuscated by T).

10 $T_{\text{cost}}(S)$ returns a measure of the execution time and space penalty added by T to S .

15 P_t maps each transformation T to the set of language constructs that T will add to the application.

Points 1 to 3 of Algorithm 1 load the application to be obfuscated, and builds appropriate internal data structures. Point 4 builds $P_s(S)$, $A(S)$, $I(S)$, and $R(M)$. Point 5 applies obfuscating transformations until the required obfuscation level has been attained or until the maximum execution time penalty is exceeded. Point 6, 25 finally, rewrites the new application A' .

Algorithm 1 (Code Obfuscation)

input: a) An application A made up of source

- code or object code files $C_1 ; C_2 ; \dots$
 \dots
 b) The standard libraries $L_1 ; L_2 ; \dots$
 \dots de-
 5 fined by the language.
 c) A set of obfuscating transformations
 $\{T_1 ; T_2 ; \dots\}$.
 d) A mapping P_t which, for each
 transformation T gives the set of
 10 language constructs that T will add to
 the application.
 e) Three functions $T_{res}(S)$, $T_{pot}(S)$,
 $T_{cost}(S)$ expressing the quality of a
 transformation T with respect to a
 15 source code object S .
 f) A set of input data $I = \{I_1; I_2; \dots$
 $\dots\}$ to A .
 g) Two numeric values $AcceptCost > 0$ and
 $ReqObf > 0$. $AcceptCost$ is a measure of the
 20 maximum extra execution time/space
 penalty the user will accept. $ReqObf$ is
 a measure of the amount of obfuscation
 required by the user.
 25 output: An obfuscated application A' made up
 of source code or object code files.

1. Load the application $C_1 ; C_2 ; \dots$ to be
 obfuscated. The obfuscator could either

- (a) load source code files, in which case the obfuscator would have to contain a complete compiler front-end performing lexical, syntactic, and semantic analysis, (a less powerful obfuscator that restricts itself to purely syntactic transformation could manage without semantic analysis) or
- (b) load object code files. If the object code retains most or all of the information in the source code (as is the case with Java class files), this method is preferable.
2. Load library code files L1; L2; . . . referenced directly or indirectly by the application.
3. Build an internal representation of the application. The choice of internal representation depends on the structure of the source language and the complexity of the transformations the obfuscator implements. A typical set of data structures might include:
- (a) A control-flow graph for each routine in A.
- (b) A call-graph for the routines in A.
- (c) An inheritance graph for the classes in A.

4. Construct mappings $R(M)$ and $P_s(S)$ (using Algorithm 5), $I(S)$ (using Algorithm 6), and $A(S)$ (using Algorithm 7).

5

5. Apply the obfuscating transformations to the application. At each step we select a source code object S to be obfuscated and a suitable transformation T to apply to S . The

10 process terminates when the required obfuscation level has been reached or the acceptable execution time cost has been exceeded.

REPEAT

15 $S := \text{SelectCode}(I);$
 $T := \text{SelectTransform}(S, A);$
 Apply T to S and update relevant data structures from point 3;

 UNTIL Done(ReqObf, AcceptCost, S , T , I).

20

6. Reconstitute the obfuscated source code objects into a new obfuscated application, A' .

Algorithm 2 (SelectCode)

25

input: The obfuscation priority mapping I as computed by Algorithm 6.

output: A source code object S .

I maps each source code object S to $I(S)$, which is a measure of how important it is to obfuscate S . To select the next source code object
5 to obfuscate, we can treat I as a priority queue. In other words, we select S so that $I(S)$ is maximized.

Algorithm 3 (SelectTransform)

10

input: a) A source code object S .
 b) The appropriateness mapping A as
 computed by Algorithm 7.

15 output: A transformation T .

Any number of heuristics can be used to select the most suitable transformation to apply to a particular source code object S . However,
20 there are two important issues to consider. Firstly, the chosen transformation must blend in naturally with the rest of the code in S . This can be handled by favoring transformations with a high appropriateness value in $A(S)$. Secondly, we want
25 to favor transformations which yield a high 'bang-for-the-buck' (i.e. high levels of obfuscation with low execution time penalty). This is accomplished by selecting transformations that maximize potency and resilience, and minimize
30 cost. These heuristics are captured by the

following code, where w_1 , w_2 , w_3 are
implementation-defined constants:

```

5      Return a transform  $T$  , such that
       $T \rightarrow V$  is within  $A(S)$ , and
       $(w_1 * T_{pot}(S) + w_2 * T_{res}(S) + w_3 * V) / T_{cost}(S)$ 
      is maximized.
```

Algorithm 4 (Done)

10

input:

- a) ReqObf, the remaining level of obfuscation.
 - b) AcceptCost, the remaining acceptable
 - 15 execution time penalty.
 - c) A source code object S .
 - d) A transformation T .
 - e) The obfuscation priority mapping I .
- 20 output:
- a) An updated ReqObf.
 - b) An updated AcceptCost.
 - c) An updated obfuscation priority mapping I .
 - d) A Boolean return value which is TRUE if
 - 25 the termination condition has been reached.

The Done function serves two purposes. It
updates the priority queue I to reflect the fact
30 that the source code object S has been obfuscated,

and should receive a reduced priority value. The reduction is based on a combination of the resilience and potency of the transformation. Done also updates ReqObf and AcceptCost, and determines
 5 whether the termination condition has been reached. w_1 , w_2 , w_3 , w_4 are implementation-defined constants:

```

      I(S) := I(S) - (w2Tpos(S) + w2Tres(S));
10    ReqObf := ReqObf - (w2Tpos(S) + w2Tres(S));
      AcceptCost := AcceptCost - Tcost(s);
      RETURN AcceptCost <= 0 OR ReqObf <= 0.
  
```

Algorithm 5 (Pragmatic Information)

15

input:

- a) An application A.
- b) A set of input data $I = \{I_1 ; I_2 ; . . . \}$ to A.

20

output:

- a) A mapping $R(M)$ which, for every routine M in A, gives the execution time rank of M .
- b) A mapping $P_s(S)$, which, for every
 25 source code object S in A, gives the set of language constructs used in S.

Compute pragmatic information. This information will be used to choose the right type

of transformation for each particular source code object.

```

1      1. Compute dynamic pragmatic information
5      (i.e., run the application under a profiler
      on the input data set I provided by the user.
      Compute R(M) (the execution time rank of M)
      for each routine/basic block, indicating
      where the application spends most of its
10     time.

      2. Compute static pragmatic information  $P_s(S)$ .
       $P_s(S)$  provides statistics on the kinds of
      language constructs the programmer used in S.
15

FOR S := each source code object in A DO
    O := The set of operators that S uses;
    C := The set of high-level language
          constructs (WHILE statements,
20     exceptions, threads, etc.) that S uses;
    L := The set of library classes/routines
          that S references;
     $P_s(S) := O \cup C \cup L$ ;
END FOR.

```

25

Algorithm 6 (Obfuscation Priority)

input:

a) An application A.

b) $R(M)$, the rank of M .

output: A mapping $I(S)$ which, for each source
code object S in A , gives the obfuscation
5 priority of S .

$I(S)$ can be provided explicitly by the user,
or it can be computed using a heuristic based on
the statistical data gathered in Algorithm 5.
10 Possible heuristics might be:

1. For any routine M in A , let $I(M)$ be
inversely proportional to the rank of M , $R(M)$.
I.e. the idea is that "if much time is
15 spent executing a routine M , then M is
probably an important procedure that should
be heavily obfuscated."

2. Let $I(S)$ be the complexity of S , as
20 defined by one of the software complexity
metrics in Table 1. Again, the (possibly
flawed) intuition is that complex code is
more likely to contain important trade
secrets than simple code.

25

Algorithm 7 (Obfuscation Appropriateness)

input:

a) An application A .

- b) A mapping P_t which, for each transformation T , gives the set of language constructs T will add to the application.
- c) A mapping $P_s(S)$ which, for each source code object S in A , gives the set of language constructs used in S .

output: A mapping $A(S)$ which, for each source code object S in A and each transformation T , gives the appropriateness of T with respect to S .

Compute the appropriateness set $A(S)$ for each source code object S . The mapping is based primarily on the static pragmatic information computed in Algorithm 5.

```

FOR S := each source code object in A DO
  FOR T := each transformation DO
    V := degree of similarity between
      Pt(T) and Ps(S);
    A(S) := A(S) U {T --> V};
  END FOR
END FOR

```

25

11 Summary and Discussion

We have observed that it may under many circumstances be acceptable for an obfuscated program to behave differently than the original one. In particular, most of our obfuscating

transformations make the target program slower or larger than the original. In special cases we even allow the target program to have different side-effects than the original, or not to terminate when the original program terminates with an error condition. Our only requirement is that the observable behavior (the behavior as experienced by a user) of the two programs should be identical.

10 Allowing such weak equivalence between original and obfuscated program is a novel and very exciting idea. Although various transformations are provided and described above, many other transformations will be apparent to one of ordinary skill in the art and can be used to provide obfuscation for enhanced software security in accordance with the present invention.

20 There is also great potential for much future research to identify transformations not yet known. In particular, we would like to see the following areas investigated:

25 1. New obfuscating transformations should be identified.

2. The interaction and ordering between different transformations should be studied. This is similar to work in code optimization, where the ordering of a sequence of

optimizing transformations has always been a difficult problem.

5 3. The relationship between potency and cost should be studied. For a particular kind of code we would like to know which transformations would give the best "bang-for-the-buck" (i.e., the highest potency at the lowest execution overhead).

10

For an overview of all the transformations that have been discussed above, see FIG. 31. For an overview of the opaque constructs that have been discussed above, see FIG. 32. However, the present invention should not be limited to the exemplary transformations and opaque constructs discussed above.

11.1 The Power of Obfuscation

20 Encryption and program obfuscation bear a striking resemblance to each other. Not only do both try to hide information from prying eyes, they also purport to do so for a limited time only. An encrypted document has a limited shelf-life: it is safe only for as long as the encryption algorithm itself withstands attack, and for as long as advances in hardware speed do not allow messages for the chosen key-length to be routinely decrypted. The same is true for an obfuscated application; it remains secret only for

30

as long as sufficiently powerful deobfuscators have yet to be built.

For evolving applications this will not be a problem, as long as the time between releases is shorter than the time it takes for the deobfuscator to catch up with the obfuscator. If this is the case, then by the time an application can be automatically deobfuscated it is already outdated and of no interest to a competitor.

However, if an application contains trade secrets that can be assumed to survive several releases, then these should be protected by means other than obfuscation. Partial server-side execution (Figure 2(b)) seems the obvious choice, but has the drawback that the application will execute slowly or (when the network connection is down) not at all.

11.2 Other Uses of Obfuscation

It is interesting to note that there may be potential applications of obfuscation other than as discussed above. One possibility is to use obfuscation in order to trace software pirates. For example, a vendor creates a new obfuscated version of his application for every new customer (We can generate different obfuscated versions of the same application by introducing an element of randomness into the SelectTransform algorithm (Algorithm 3). Different seeds to the random number generator will produce different versions.)

and keeps a record of to whom each version was sold. This is probably only reasonable if the application is being sold and distributed over the net. If the vendor finds out that his application
5 is being pirated, all he needs to do is to get a copy of the pirated version, compare it against the data base, and see who bought the original application. It is, in fact, not necessary to store a copy of every obfuscated version sold. It
10 suffices to keep the random number seed that was sold.

Software pirates could themselves make (illicit) use of obfuscation. Because the Java obfuscator we outlined above works at the bytecode
15 level, there is nothing stopping a pirate from obfuscating a legally bought Java application. The obfuscated version could then be resold. When faced with litigation the pirate could argue that he is, in fact, not reselling the application that
20 he originally bought (after all, the code is completely different!), but rather a legally reengineered version.

25 Conclusion

In conclusion, the present invention provides a computer implemented method and apparatus for preventing, or at least hampering, reverse engineering of software. While this may be effected at the expense
30 of execution time or program size with the resulting

transformed program behaving differently at a detailed level, it is believed that the present technique provides significant utility in appropriate circumstances. In one embodiment, the transformed
5 program has the same observable behavior as the untransformed program. Accordingly, the present invention allows for such weak equivalence between the original and obfuscated program.

While the present discussion has been primarily in
10 the context of hampering reverse engineering of software, other applications are contemplated such as watermarking software objects (including applications). This exploits the potentially distinctive nature of any single obfuscation procedure. A vendor would create a
15 different obfuscated version of an application for every customer sold. If pirate copies are found, the vendor need only compare it against the original obfuscation information database to be able to trace the original application.

20 The particular obfuscation transformations described herein are not exhaustive. Further obfuscation regimes may be identified and used in the present novel obfuscation tool architecture.

Where in the foregoing description reference has
25 been made to elements or integers having known equivalents, then such equivalents are included as if they were individually set forth.

Although the present invention has been described by way of example and with reference to particular
30 embodiments. It is to be understood that modifications

and improvements can be made without departing from the scope of the present invention.

CLAIMS

What is claimed is:

- 5 1. A computer implemented method for obfuscating
code, comprising:
 selecting a subset of the code to obfuscate;
 selecting an obfuscating transform to apply;
 and
10 applying the transformation, wherein the
transformed code provides weak equivalence to the
untransformed code.
2. The computer implemented method of Claim 1,
15 further comprising:
 identifying one or more source code input
files corresponding to source code for the code of
an application to be processed;
 selecting a required level of obfuscation
20 (the potency);
 selecting a maximum execution time or space
penalty (the cost);
 reading and parsing the input files;
 providing information identifying data types,
25 data structures, and control structures used by
the application to be processed;
 selecting and applying obfuscating
transformations to source code objects until the
required potency has been achieved or the maximum
30 cost has been exceeded; and

outputting the transformed code of the application.

3. The method of Claim 1, wherein the
5 transformation comprises an opaque construct, the opaque construct being constructed using aliasing and concurrency techniques.

4. The method of Claim 1, further comprising:
10 outputting information about obfuscating transformations applied to the obfuscated code and information relating obfuscated code of a transformed application to source code of the application.

15 5. The method of Claim 1, wherein the transformation is selected to preserve the observable behavior of the code of an application.

20 6. The method of Claim 1, further comprising: deobfuscating the code, the deobfuscating the code comprising removing any obfuscations from the obfuscated code of an application by use of slicing, partial evaluation, dataflow analysis, or
25 statistical analysis.

7. A computer program embodied on a computer-readable medium for obfuscating code, comprising:
logic that selects a subset of the code to
30 obfuscate;

logic that selects an obfuscating transform to apply; and

logic that applies the transformation, wherein the transformed code provides weak
5 equivalence to the untransformed code.

8. The computer program of Claim 7, further comprising:

logic that identifies one or more source code
10 input files corresponding to source code for the code of an application to be processed;

logic that selects a required level of obfuscation (the potency);

logic that selects a maximum execution time
15 or space penalty (the cost);

logic that reads and parses the input files;

logic that provides information identifying data types, data structures, and control
structures used by the application to be
20 processed;

logic that selects and applies obfuscating transformations to source code objects until the required potency has been achieved or the maximum cost has been exceeded; and

25 logic that outputs the transformed code of the application.

9. The computer program of Claim 7, wherein the transformation comprises an opaque construct, the

opaque construct being constructed using aliasing and concurrency techniques.

10. The computer program of Claim 7, further
5 comprising:

logic that outputs information about
obfuscating transformations applied to the
obfuscated code and information relating
obfuscated code of a transformed application to
10 source code of the application.

11. The computer program of Claim 7, wherein the
transformation is selected to preserve the observable
behavior of the code of an application.

15

12. The computer program of Claim 7, further
comprising:

logic that deobfuscates the code, the
deobfuscating the code comprising removing any
20 obfuscations from the obfuscated code of an
application by use of slicing, partial evaluation,
dataflow analysis, or statistical analysis.

13. An apparatus for obfuscating code,
25 comprising:

means for selecting a subset of the code to
obfuscate;

means for selecting an obfuscating transform
to apply; and

means for applying the transformation,
wherein the transformed code provides weak
equivalence to the untransformed code.

5 14. The apparatus of Claim 13, further
comprising:

means for identifying one or more source code
input files corresponding to source code for the
code of an application to be processed;

10 means for selecting a required level of
obfuscation (the potency);

means for selecting a maximum execution time
or space penalty (the cost);

15 means for reading and parsing the input
files;

means for providing information identifying
data types, data structures, and control
structures used by the application to be
processed;

20 means for selecting and applying obfuscating
transformations to source code objects until the
required potency has been achieved or the maximum
cost has been exceeded; and

25 means for outputting the transformed code of
the application.

15. The apparatus of Claim 13, wherein the
transformation comprises an opaque construct, the
opaque construct being constructed using aliasing and
30 concurrency techniques.

16. The apparatus of Claim 13, further comprising:

5 means for outputting information about obfuscating transformations applied to the obfuscated code and information relating obfuscated code of a transformed application to source code of the application.

10 17. The apparatus of Claim 13, wherein the transformation is selected to preserve the observable behavior of the code of an application.

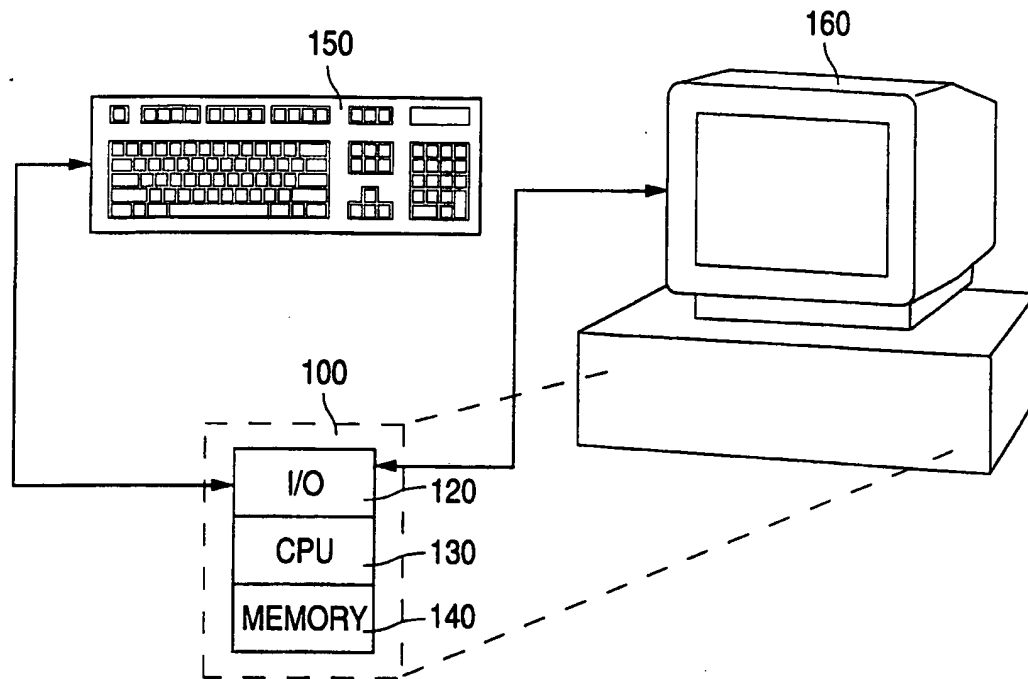
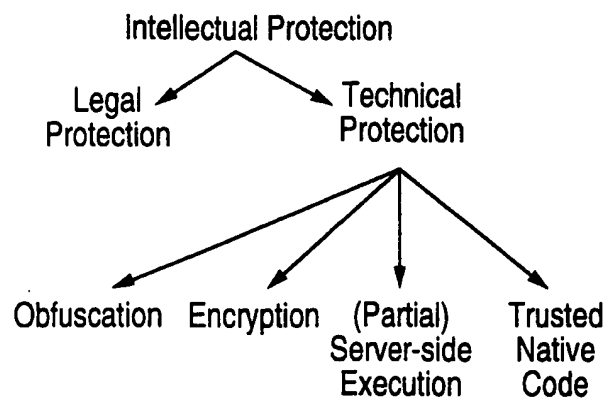
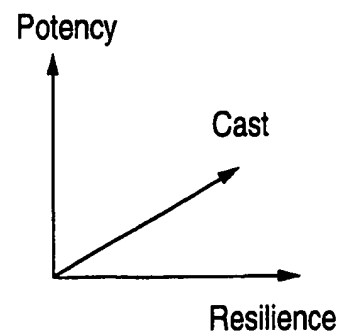
18. The apparatus of Claim 13, further comprising:

15 means for deobfuscating the code, the deobfuscating the code comprising removing any obfuscations from the obfuscated code of an application by use of slicing, partial evaluation, dataflow analysis, or statistical analysis.

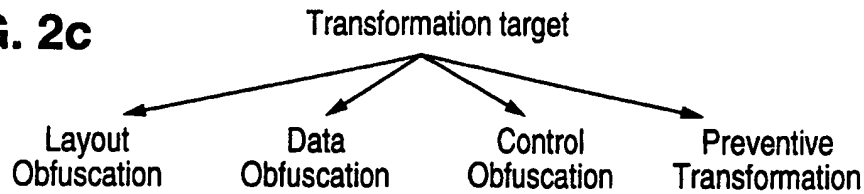
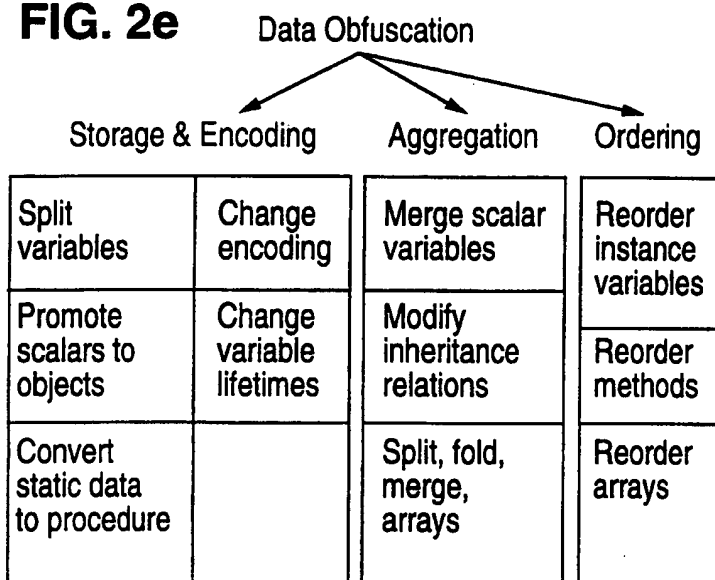
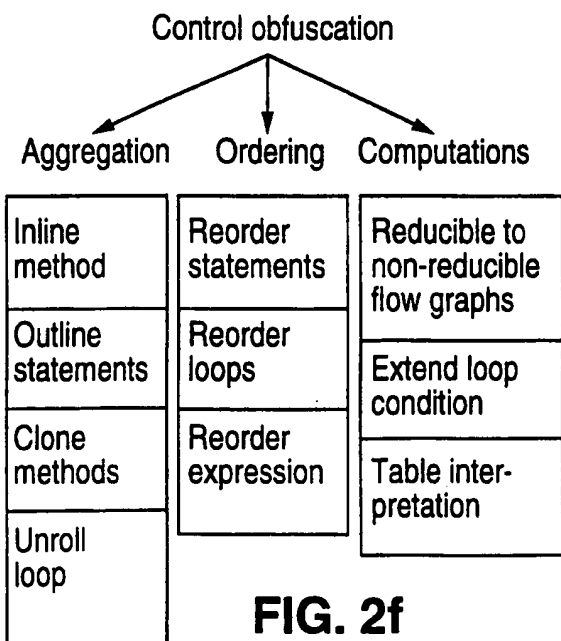
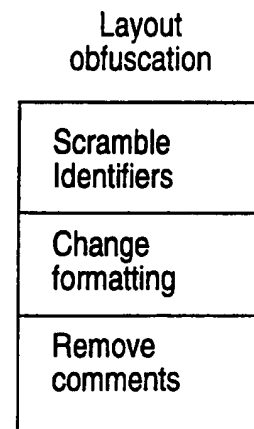
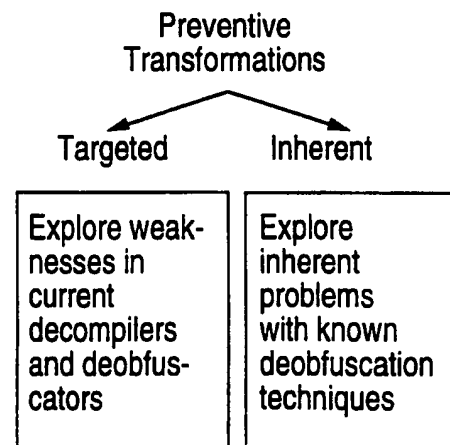
19. The apparatus of Claim 13, wherein the code comprises Java™ bytecode.

25 20. The apparatus of Claim 13, wherein the transformation provides a data obfuscation, a control obfuscation, or a preventive obfuscation.

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**FIG. 1****FIG. 2a****FIG. 2b**

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FIG. 2c**FIG. 2e****FIG. 2d****FIG. 2f****FIG. 2g**

3/27

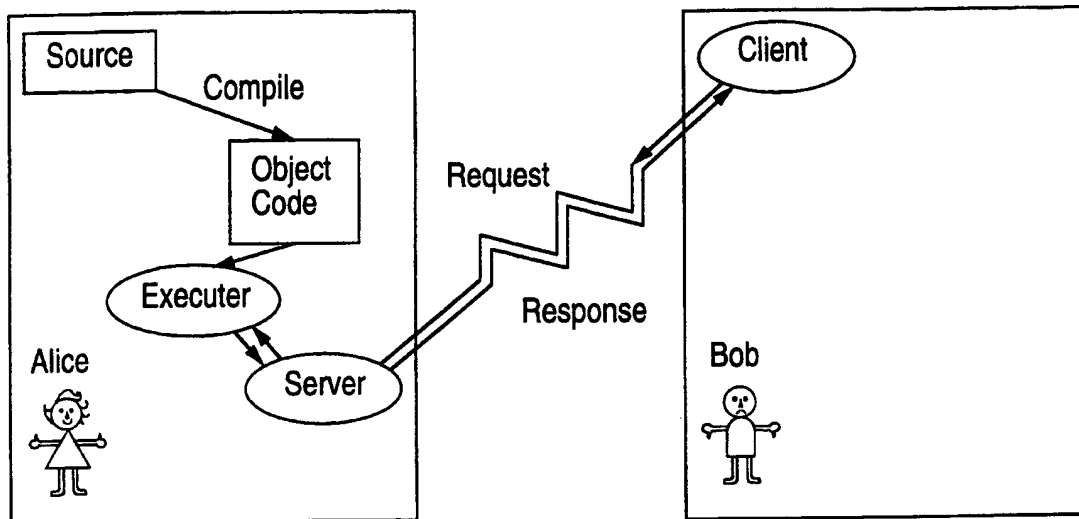


FIG. 3a

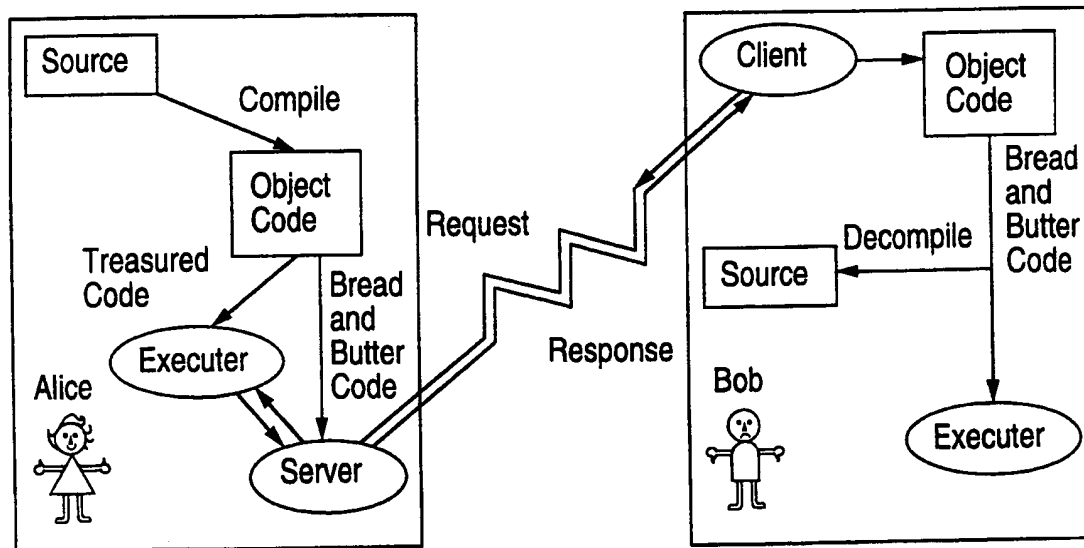


FIG. 3b

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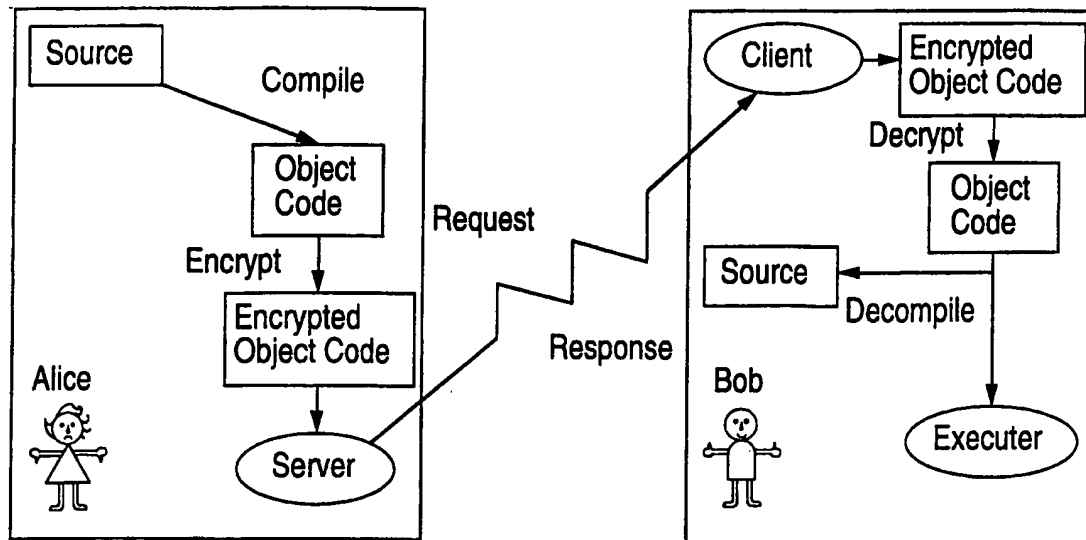


FIG. 4a

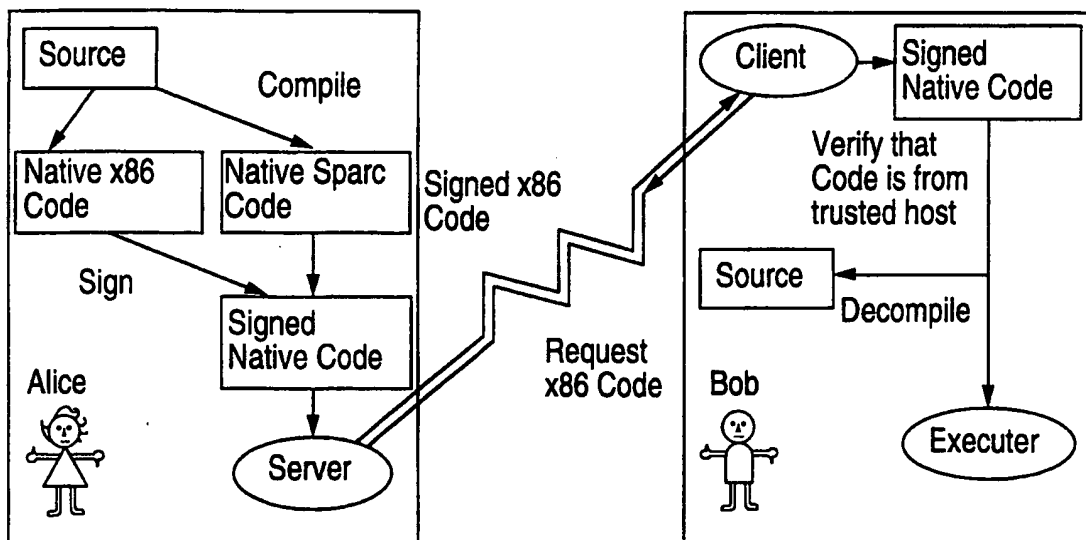
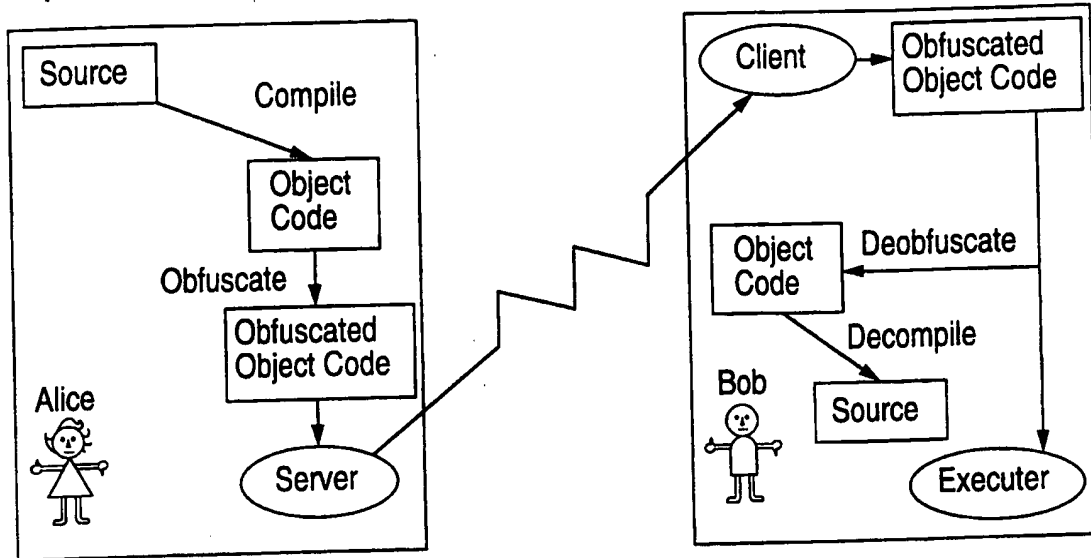


FIG. 4b

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**FIG. 5**

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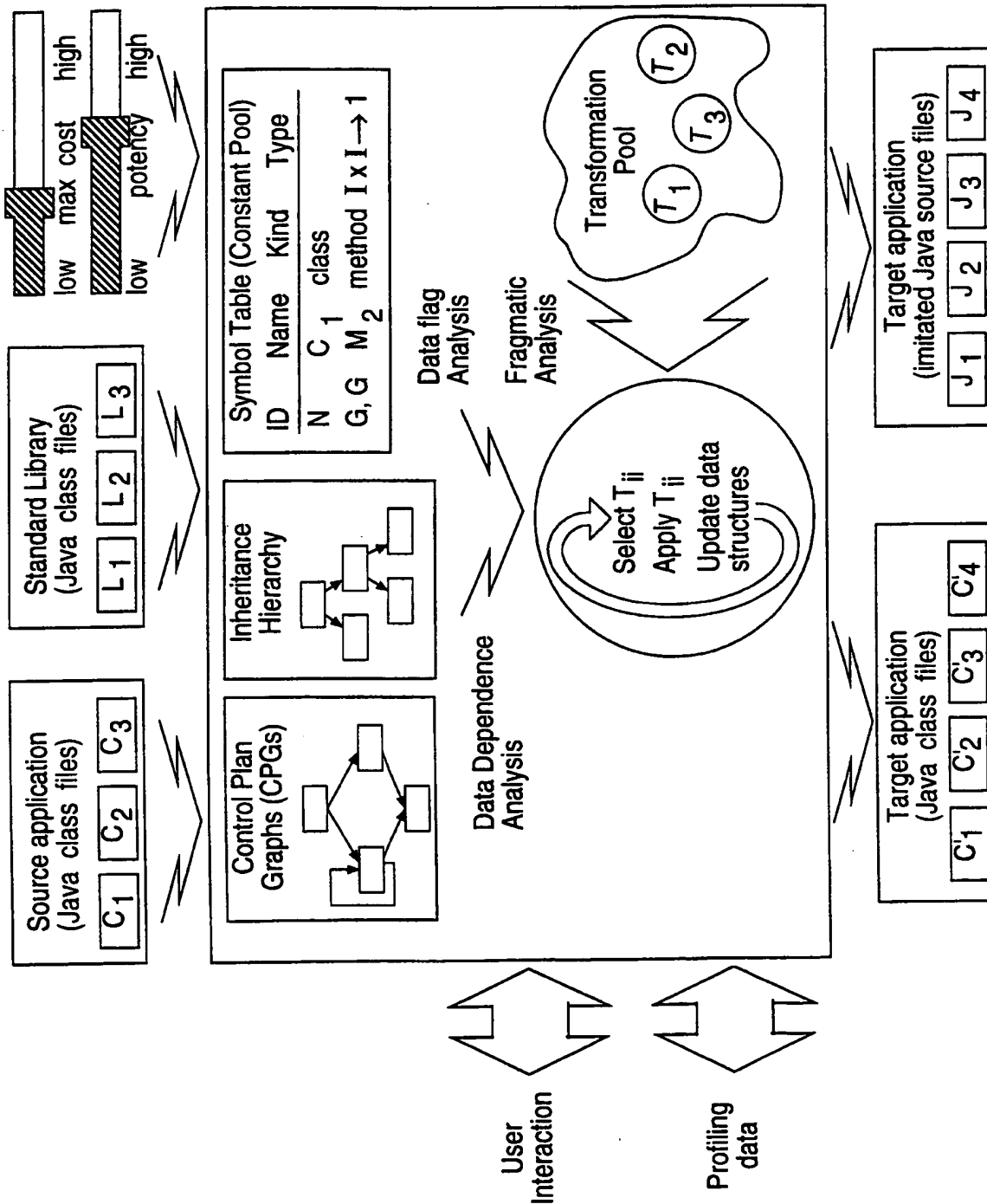


FIG. 6

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METRIC	METRIC NAME	CITATION
μ_1	Program Length $E(P)$ increases with the number of operators and operands in P .	Halstead
μ_2	Cyclomatic Complexity $E(F)$ increases with the number of predicates in F .	McCabe
μ_3	Nesting Complexity $E(F)$ increases with the nesting level of conditionals in F .	Harrison
μ_4	Data Flow Complexity $E(F)$ increases with the number of inter-basic block variable references in F .	Oviedo
μ_5	Fan-in/out Complexity $E(F)$ increases with the number of formal parameters to F , and with the number of global data structures read or updated by F .	Henry
μ_6	Data Structure Complexity $E(P)$ increases with the complexity of the static data structures declared in P . The complexity of a scalar variable is constant. The complexity of an array increases with the number of dimensions and with the complexity of the element type. The complexity of a record increases with the number and complexity of its fields.	Munson
μ_7	OO Metric $E(C)$ increases with (μ_7^a) the number of methods in C , (μ_7^b) the depth (distance from the root) of C in the inheritance tree, (μ_7^c) the number of direct subclasses of C , (μ_7^d) the number of other classes to which C is coupled*, (μ_7^g) the number of methods that can be executed in response to a message sent to an object of C , (μ_7^f) the degree to which C 's methods do not reference the same set of instance variables. Note: μ_7^f measures cohesion; i.e., how strongly related the elements of a module are.	Chidamber

*Two classes are coupled if one uses the methods or instance variables of the other.

FIG. 7

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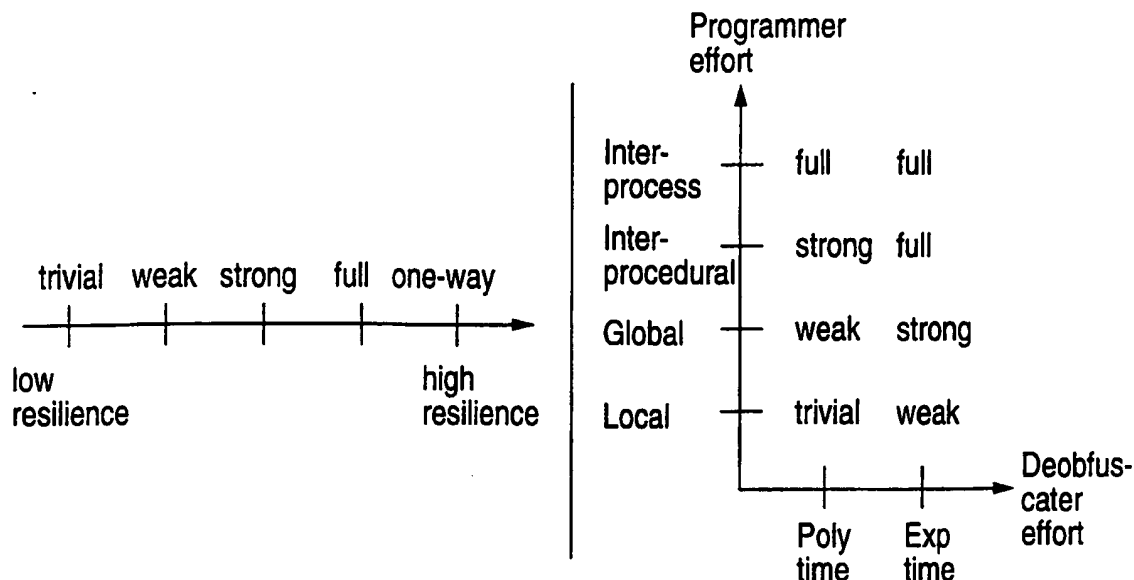


FIG. 8a

FIG. 8b

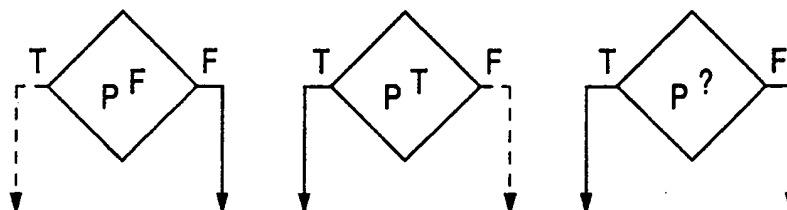


FIG. 9

```
{
  int v, a=5; b=6;
  v=11 = a + b;
  if (b > 6) T ...
  if (random (1,5) < 0) F...
}
```

FIG. 10a

```
{
  int v, a=5; b=6;
  if (...) ...
  : (b is unchanged)
  if (b < 7) T a++1
  v=11 = (a > 5) 7v=b=b; v=b
}
```

FIG. 10b

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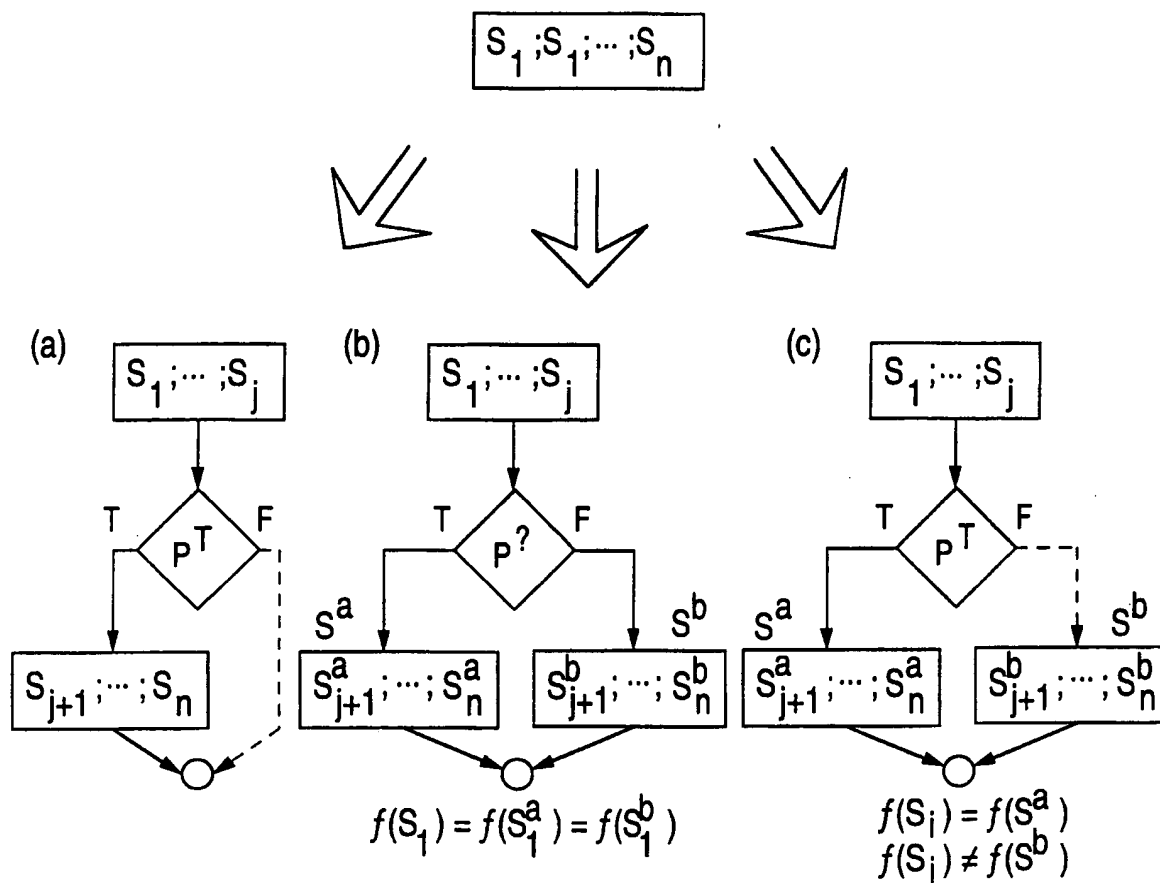


FIG. 11

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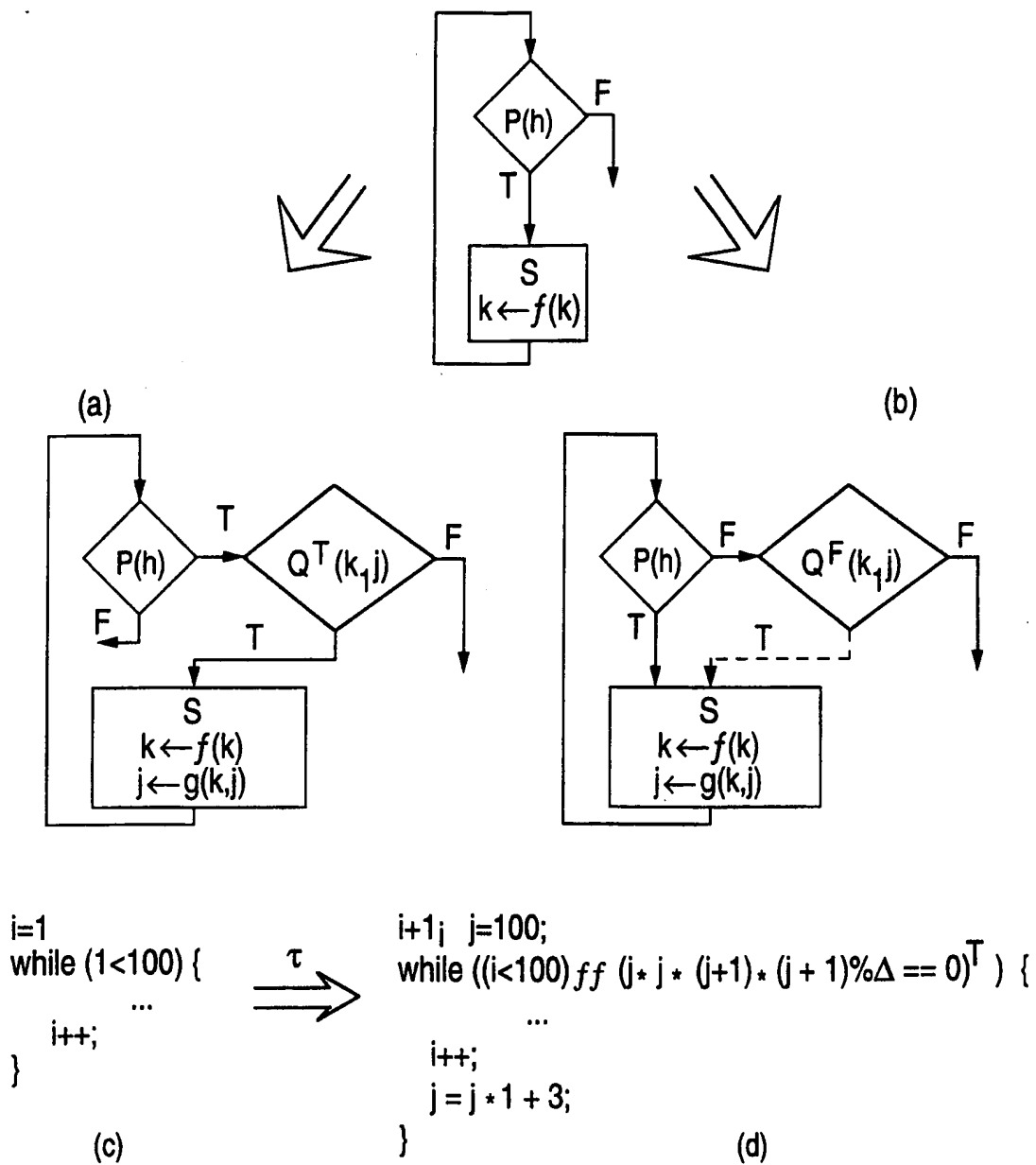
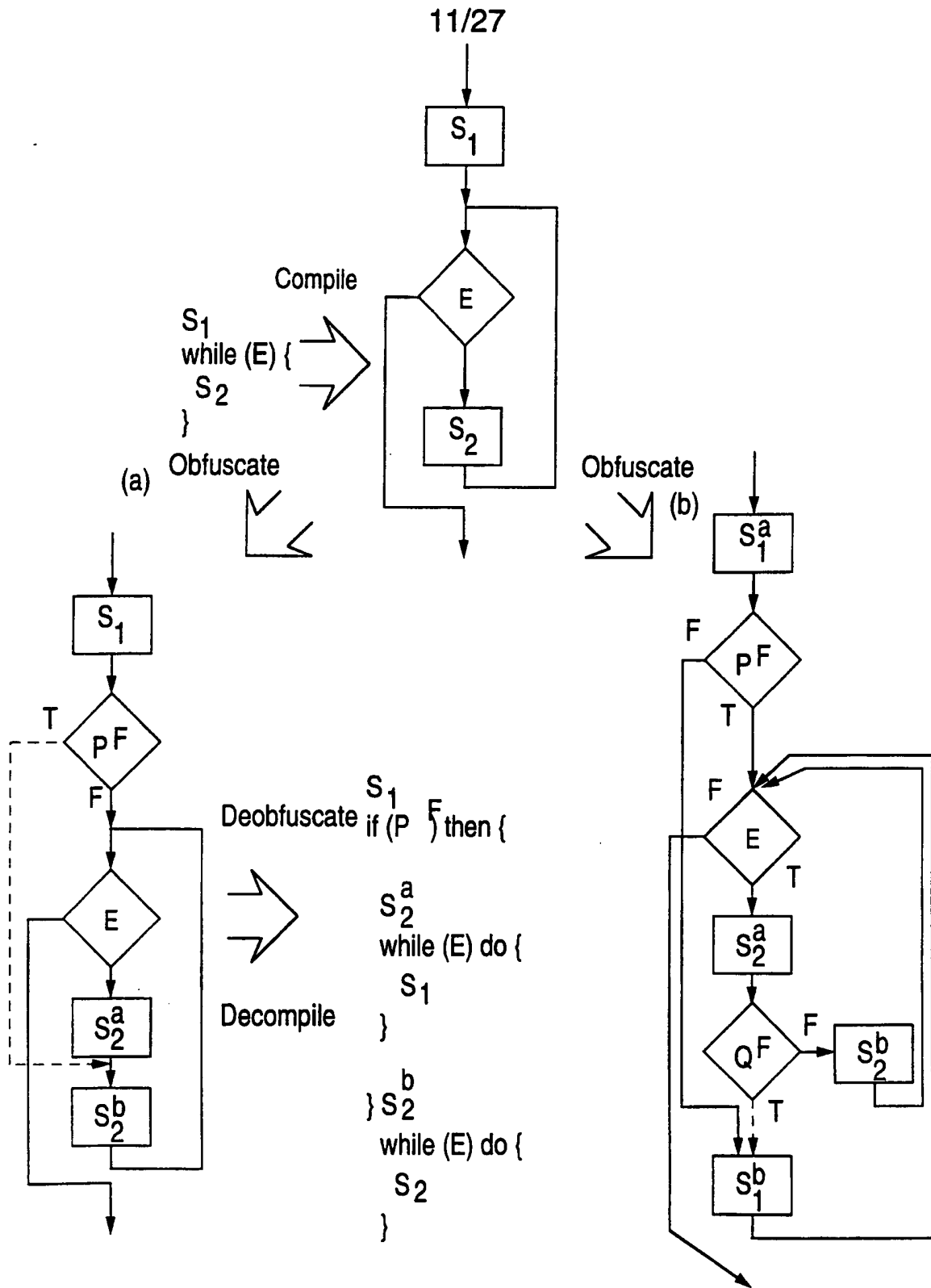


FIG. 12



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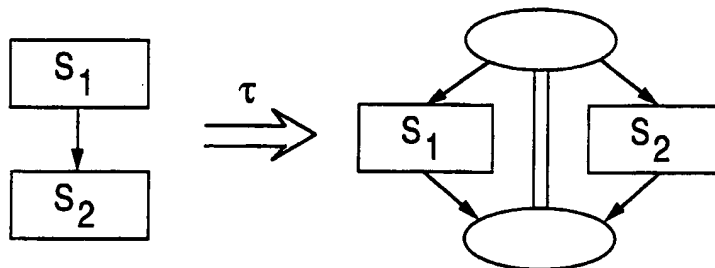


FIG. 14

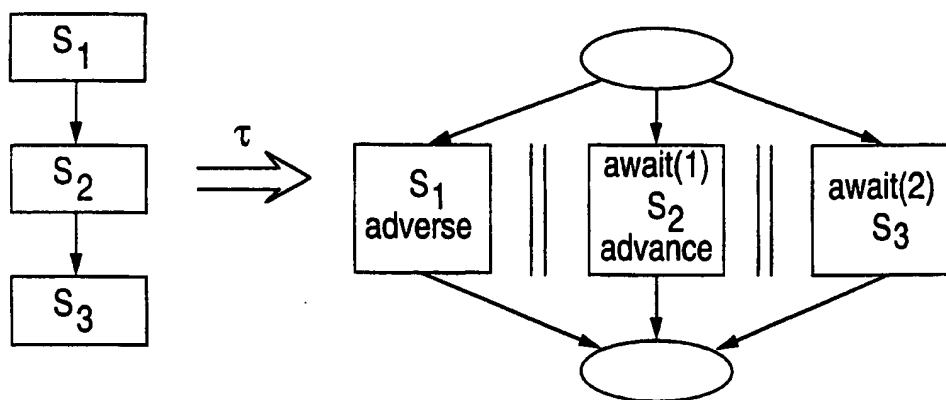


FIG. 15

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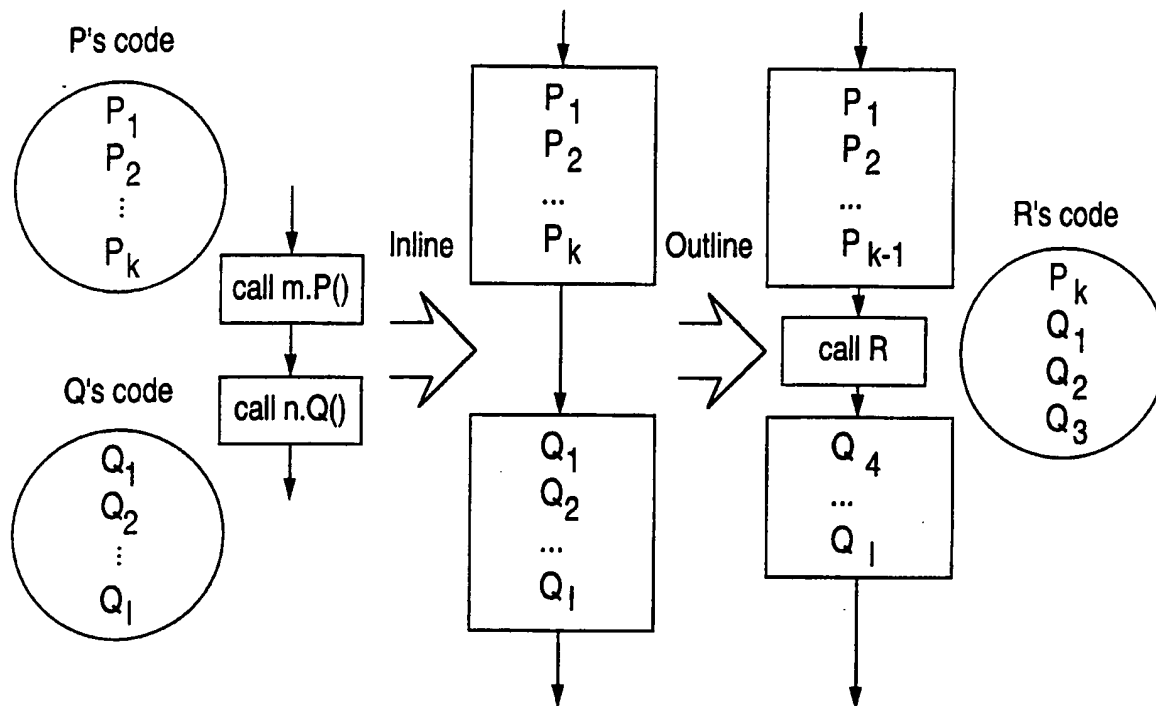


FIG. 16

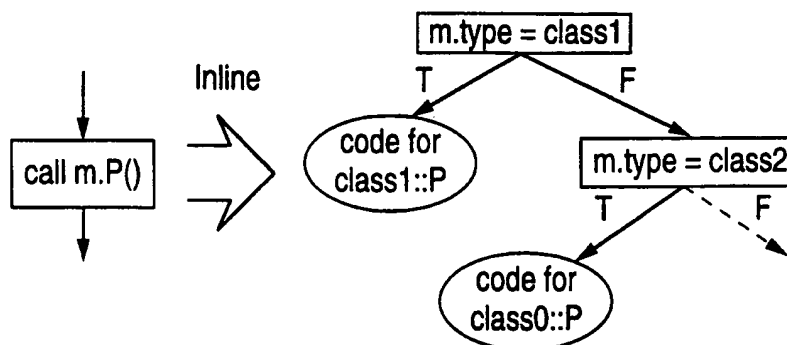


FIG. 17

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<pre> class C { method M1 (T1 a) { S₁^{M1}; ... S_k^{M1}; } method M2 (T1 b; T2 c) { S₁^{k1}; ... S_m^{k2}; } } { C x=new C; x.M1(a); x.M2(b, c); }</pre>	$\xRightarrow{\tau}$	<pre> class C' { method M (Ti a; T2 c; int V) { if (V==p) {S₁^{M1}; ... S_k^{M1}; } else {S₁^{M1}; ... S_m^{k2}; } } } { C' x=new C'; x.M(a, c, V=^p); x.M(b, c, V=^g); }</pre>
--	----------------------	---

FIG. 18

<pre> class C { method m (int x) {S₁ ... S_k} } { C x = new C; x.m(8); ... x.m(7); }</pre>	$\xRightarrow{\tau}$	<pre> class C1 { method m (int x) {S₁^a ... S_n^a } method m1 (int x) {S₁^c ... S_n^c } } class C2 inherits C1 { method M (int x) {S₁^b ... S_k^b } } { C1 x; if (P7) x=new C1 else x=new C2; x.m(5); ...; x.m1(7); }</pre>
--	----------------------	--

FIG. 19

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FIG. 20a

```

for (i=1, i<=n, i++)
  for (j=1, j<=n, j++)
    a[1,j]=b[j,i]
  
```

 $\xRightarrow{\tau}$

```

for (I=1, I<=n, I+=64)
  for (J=1, J<=n, J+=64)
    for (i=I, i<=min(I+63,n), i++)
      for (j=J, j<=min(J+63,n), j++)
        a[i,j]=b[j,i]
  
```

FIG. 20b

```

for (i=2, i<(n-1), i++)
  a[i] += a[1-i] == [i+1]
  
```

 $\xRightarrow{\tau}$

```

for (i=2, i<(n-2), i+=2) {
  a[i] += n[i-1]=a[i+1];
  a[i+1] += a[i]=a[i+2];
};
if (((n-2) % 2) == 1)
  x[n-1] += a[n-2]=a[n]
  
```

FIG. 20c

```

for (i=1, i<n, i++) {
  a[i] += c;
  x[i+1]=d+x[i+1]=a[i]
}
  
```

 $\xRightarrow{\tau}$

```

for (i=1, i<n, i++)
  a[i] += c;
for (i=1, i<n, i++)
  x[i+i] <d+x[i+1]=a[i]
  
```

FIG. 21a

g(V)		f(p,q)	
p	q	V	2p+q
0	0	False	0
0	1	True	1
1	0	True	2
1	1	False	3

FIG. 21b

p	
VAL[p,q]	
0	0 1
1	1 0

FIG. 21c

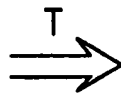
AND[A,B]		A			
		0	1	2	3
B	0	3	0	0	0
	1	3	1	2	3
	2	0	2	1	3
	3	3	0	0	3

FIG. 21d

		A			
		0	1	2	3
B	OR[A,B]	0	1	2	3
	0	3	1	2	3
	1	1	1	2	2
	2	2	2	1	1
	3	0	1	2	0

```

(1)  bool A,B,C;
(2)  A = True;
(3)  B = False;
(4)  C = False;
(5)  C = A & B;
(6)  C = A & B;
(7)  C = A | B;
(8)  if (A) ...;
(9)  if (B) ...;
(10) if (C) ...;
  
```



```

(1') short a1,a2,b1,b2,c1,c2;
(2') a1=0; a2=1;
(3') b1=0; b2=0;
(4') c1=1; c2=1;
(5') x=AND[2*a1+a2,2*b1+b2]; c1=x/2; c2=x%2;
(6') c1=(a1 ^ a2) & (b1 ^ b2); c2=0
(7') x=OR[2*a1+a2,2*b1+b2]; c1=x/2; c2=x%2;
(8') x=2*a1+a2; if ((x==1) || (x==2) ...)
(9') if (b1 ^ b2) ...;
(10') if (VAL[c1,c2]) ...;
  
```

FIG. 21e

SUBSTITUTE SHEET (RULE 26)

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```

String G (int n) {
    int i=0,k;
    String B;
    while (i) {
        L1: if (n==1) {S[i++]="A";k=0;goto L6};
        L2: if (n==2) {S[i++]="B";k= -2 ;goto L6};
        L3: if (n==3) {S[i++]="C";goto L8};
        L4: if (n==4) {S[i++]="K";goto L9};
        L5: if (n==5) {S[i++]="C";goto L11};
            if (n>12) goto L1;
        L6: if (k++<=2) {S[i++]="A";goto L6} else goto L8;
        L8: return S;
        L9: S[i++]="C"; goto L10;
        L10: S[i++]="B"; goto L8;
        L11: S[i++]="C"; goto L12;
        L12: goto L10;
    }
}

```

FIG. 22**FIG. 23a**

$$\begin{aligned}
 Z(X+r,Y) &= 2^{32} \cdot Y + (r+X) = Z(X,Y) + r \\
 Z(X,Y+r) &= 2^{32} \cdot (Y+r) + X = Z(X,Y) + r \cdot 2^{32} \\
 Z(X \cdot r,Y) &= 2^{32} \cdot Y + X + r = Z(X,Y) + (r-1) \cdot X \\
 Z(X,Y \cdot r) &= 2^{32} \cdot Y \cdot r + X = Z(X,Y) + (r-1) \cdot 2^{32} \cdot Y
 \end{aligned}$$

FIG. 23b

(1) int X=45, Y=95;	τ	(1') long Z=167759066119551045;
(2) X += 5;	\Rightarrow	(2') Z += 5;
(3) Y += 11;		(3') Z += 47244640256;
(4) X *= c;		(4') z += (c-1) * (Z & 4294967295);
(5) Y *= d;		(5') Z += (d-1) * (Z & 18446744069414584320);

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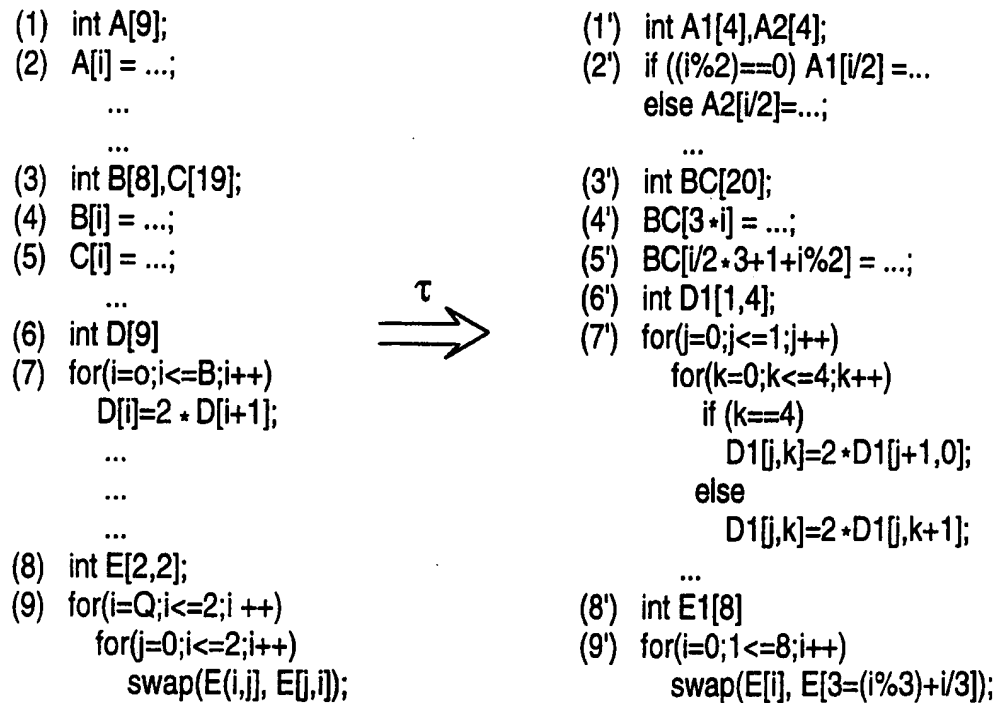
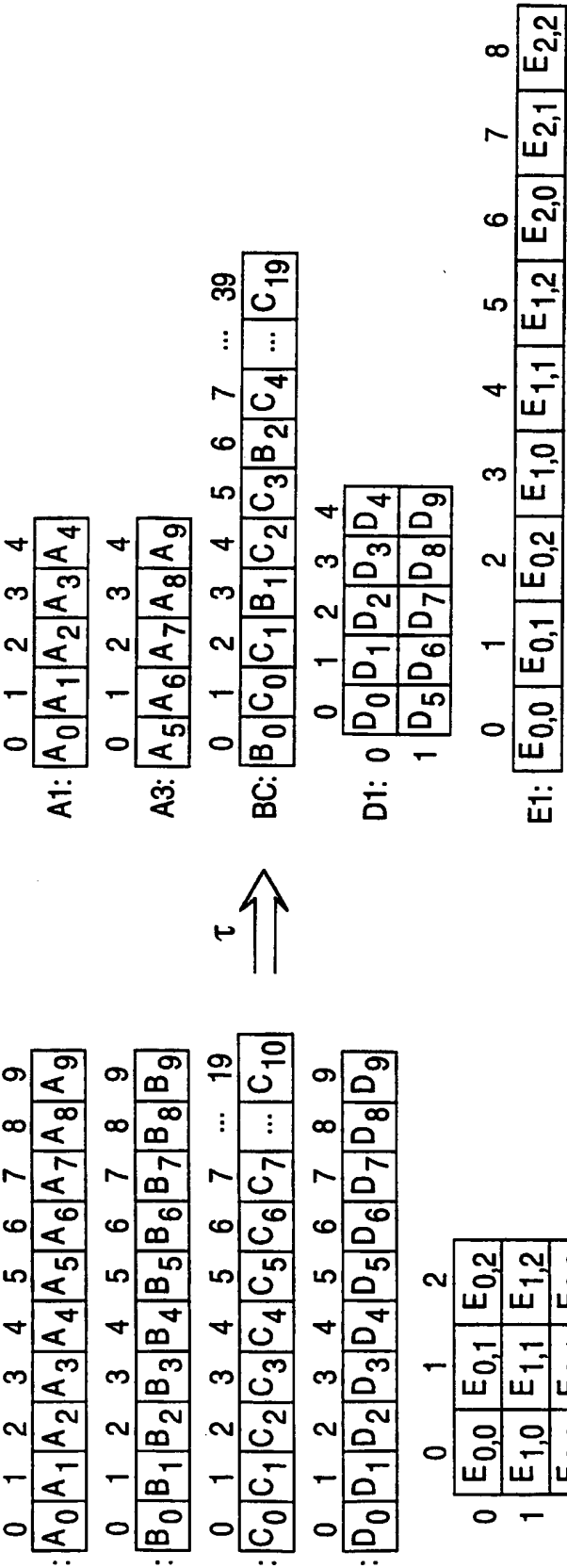


FIG. 24a



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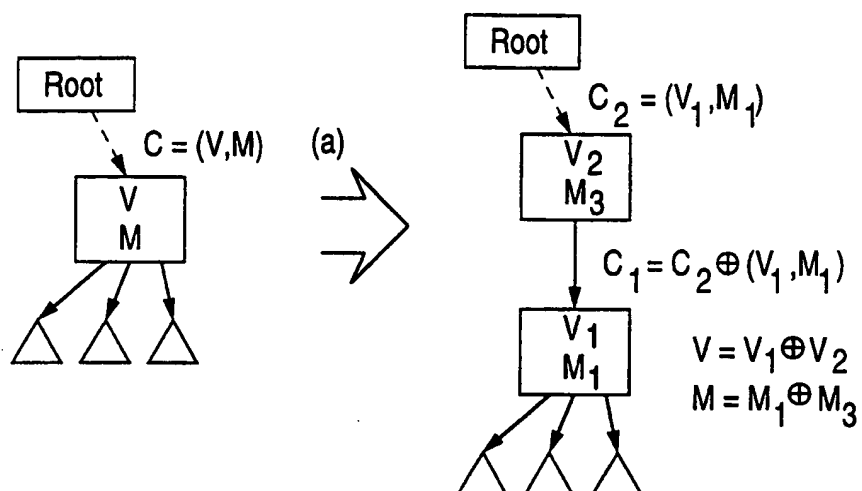


FIG. 25a

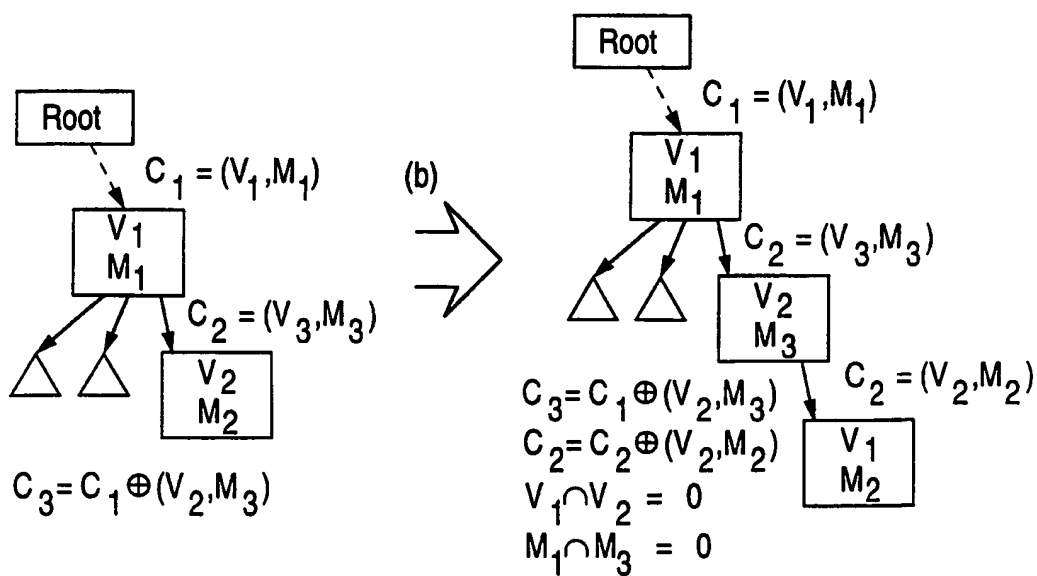


FIG. 25b

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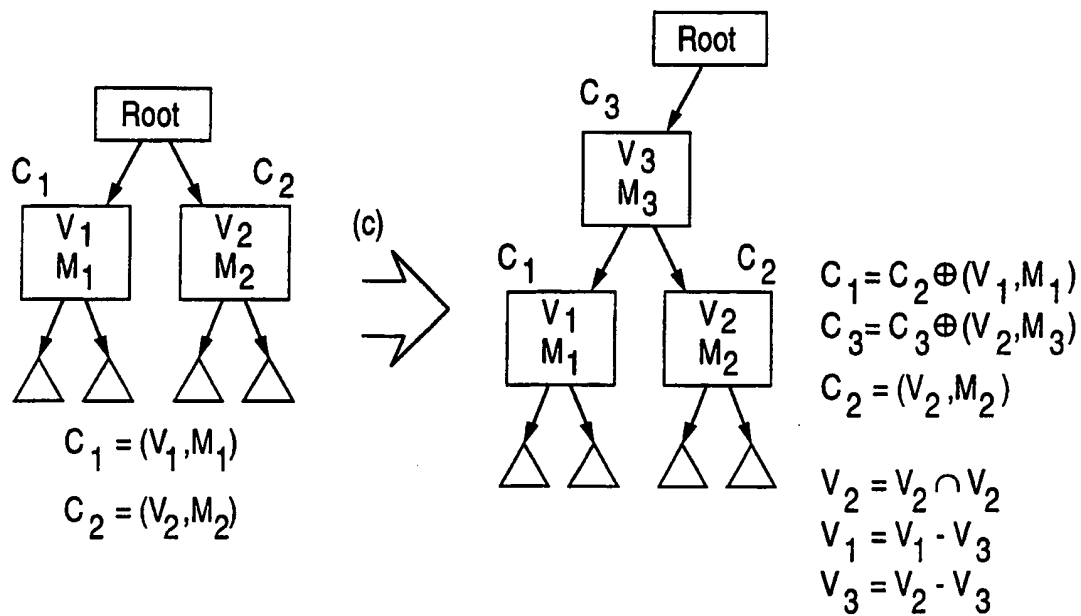


FIG. 25c

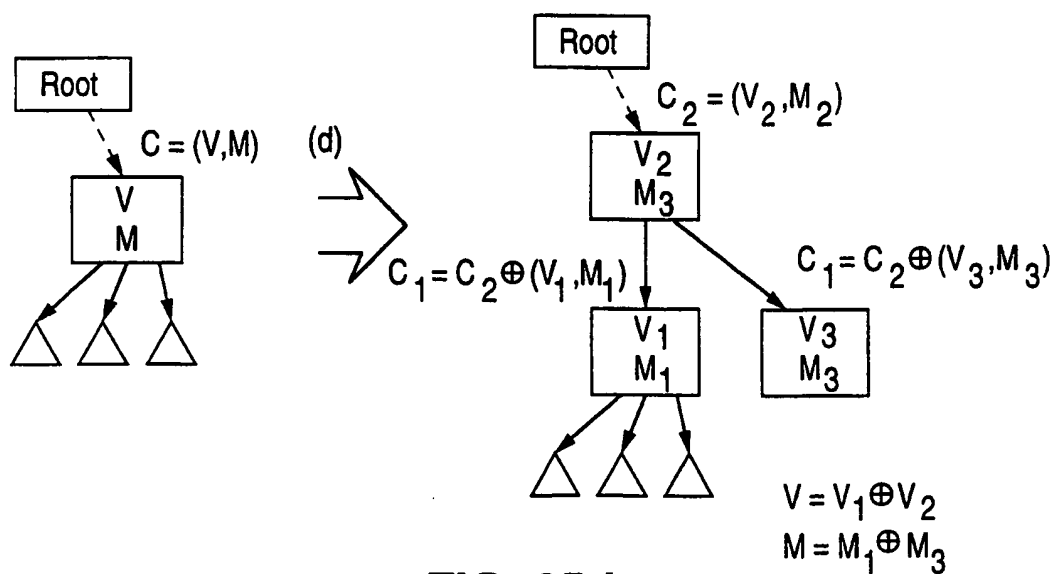
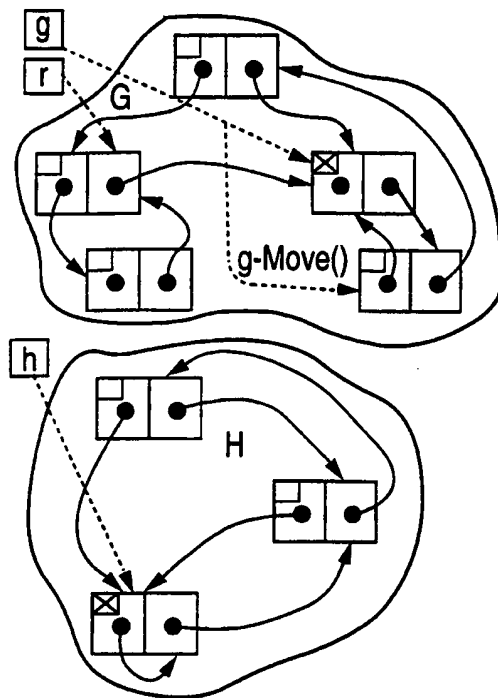


FIG. 25d

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```

Node g, h;
method P(...,Node f) {
  /* 1 */ g = g.Move();
             h = h.Move();
  /* 2 */ h = h.Insert(new Node);
             ⋮
  /* 3 */ x.R(...,f.Move());
             ⋮
  /* 4 */ if (f==g) ? ...
             ⋮
  /* 5 */ if (g==h) F ...
             ⋮
  /* 6 */ f.Token=False;
             g.Token=True;

  /* 7 */ if (f.Token)? ...
             ⋮
  /* 8 */ f.Token=True;
             h.Token=False;

  /* 9 */ if (f.Token)T ...
}

```

FIG. 26

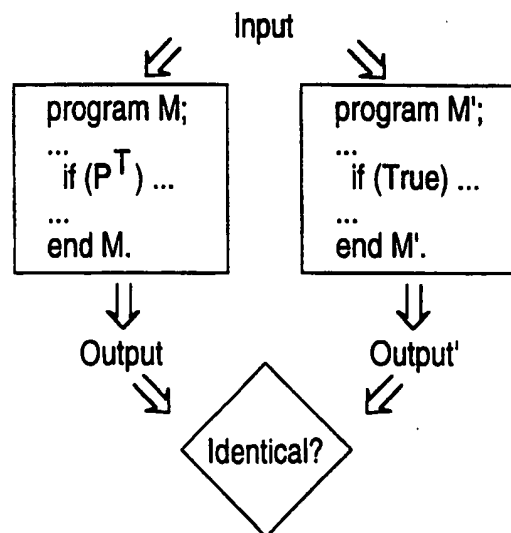


FIG. 30

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```

thread S {
  int R;
  while (1) {
    R = random(1,C);
    X = R*R;
    sleep(3);
  }
}

thread T {
  int R;
  while (i) {
    R = random(1,C);
    X = 7*R*R;
    sleep(2);
    X *= X;
    sleep(5);
  }
}

int X, Y;
const C = sqrt(maxint)/10;
main () {
  S.run(); T.run();
  ...
  if ((Y - 1) == X) F <= P
  ...
}

```

FIG. 27

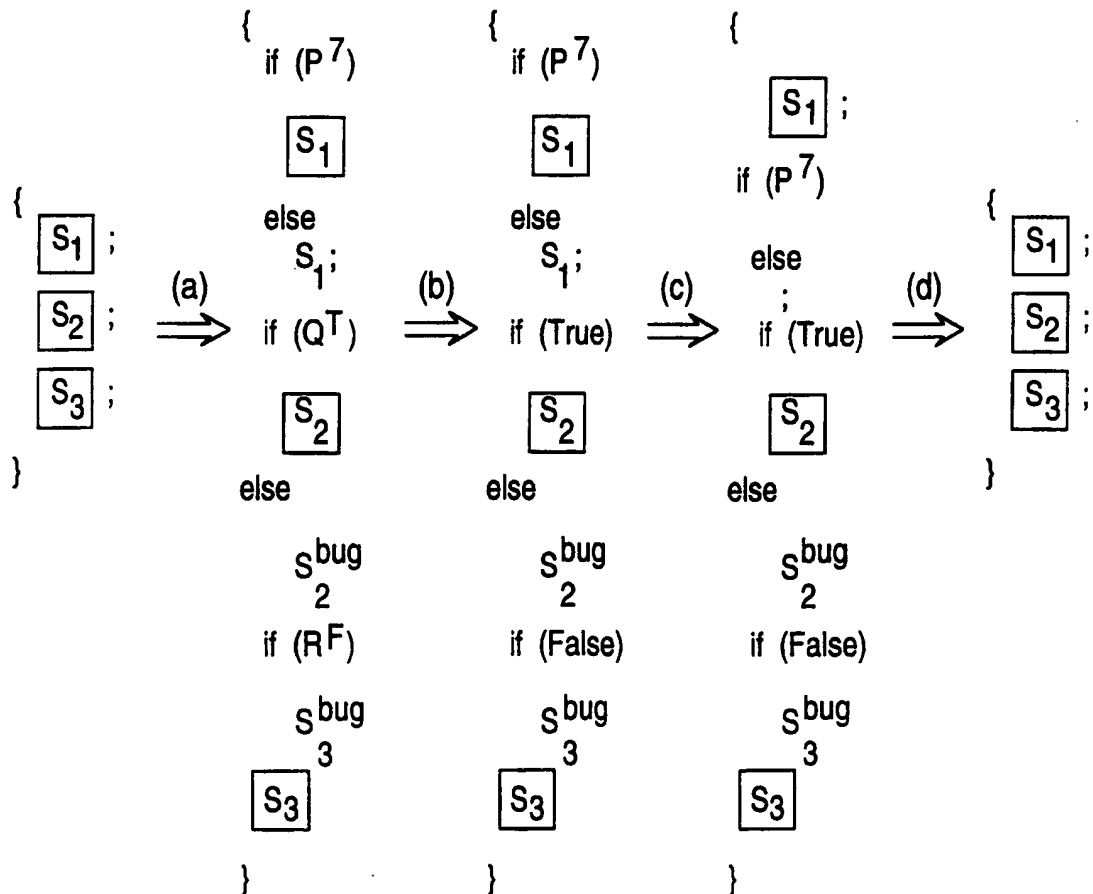


FIG. 28

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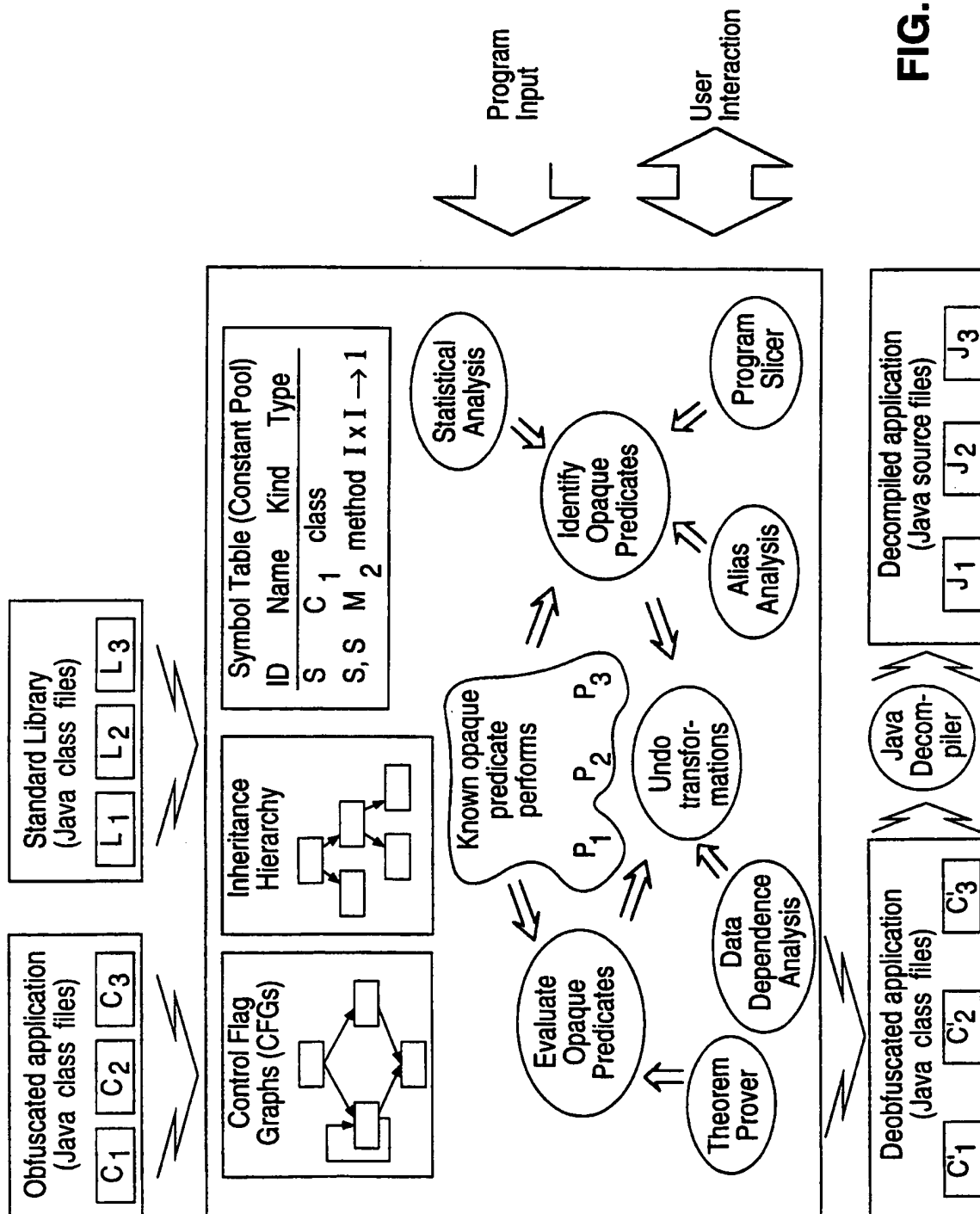


FIG. 29

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TARGET OPERATION	OBFUSCATION TRANSFORMATION	POTENCY	QUALITY RESILIENCE	COST	METRICS	SECTION
Layout	Scramble Identifiers	medium	one-way	free		5.5
	Change Formatting	low	one-way	free		5.5
	Remove Comments	high	one-way	free		5.5
Control Computations	Insert Dead or Irrelevant Code	Depends on the quality of the opaque predicate and the nesting depth at which the construct is inserted.			$\mu 1, \mu 2, \mu 3$	6.2.1
	Extend Loop Condition				$\mu 1, \mu 2, \mu 3$	6.2.2
	Reducible to Non-Reducible				$\mu 1, \mu 2, \mu 3$	6.2.3
	Add Redundant Operands				$\mu 1$	6.2.6
	Remove Programming Idioms	medium	strong	†	$\mu 1$	6.2.4
	Table Interpretation	high	strong	costly	$\mu 1$	6.2.5
	Inline Method	medium	one-way	free	$\mu 1$	6.3.1
Aggregation	Outline Statements	medium	strong	free	$\mu 1$	6.3.1
	Interleave Methods	Depends on the quality of the opaque predicate.			$\mu 1, \mu 2, \mu 3$	6.3.2
	Clone Methods				$\mu 1, \mu 7$	6.3.3
	Block Loop	low	weak	free	$\mu 1, \mu 2$	6.3.4
	Unroll Loop	low	weak	cheap	$\mu 1$	6.3.4
	Loop Fission	low	weak	free	$\mu 1, \mu 2$	6.3.4
	Reorder Statements	low	one-way	free		6.4
Ordering	Reorder Loops	low	one-way	free		6.4
	Reorder Expression	low	one-way	free		6.4

FIG. 31a-1

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TARGET OPERATION	OBFUSCATION		TRANSFORMATION	QUALITY		METRICS	SECTION
	OPERATION	TRANSFORMATION	POTENCY	RESILIENCE	COST		
Data Storage & Encoding		Change Encoding	Depends on the complexity of the encoding function.			$\mu 1$	7.1.1
		Promote Scalar to Object	low	strong	free		7.1.2
		Change Variable Lifetime	low	strong	free	$\mu 4$	7.1.2
		Split Variable	Depends on the number of variables into which the original variable is split.			$\mu 1$	7.1.3
Aggregation		Convert Static to Procedural Data	Depends on the complexity of the generated function.			$\mu 1, \mu 2$	7.1.4
		Merge Scalar Variables	low	weak	free	$\mu 1$	7.2.1
		Factor Class	medium	†	free	$\mu 1, \mu 7b, c, e$	7.2.3
		Insert Bogus Class	medium	†	free	$\mu 1, \mu 7b, c$	7.2.3
		Refactor Class	medium	†	free	$\mu 1, \mu 7b, c, e$	7.2.3
		Split Array	†	weak	free	$\mu 1, \mu 2, \mu 6$	7.2.2
		Merge Arrays	†	weak	free	$\mu 1, \mu 3$	7.2.2
		Fold Array	†	weak	cheap	$\mu 1, \mu 2, \mu 3, \mu 6$	7.2.2
Ordering		Flatten Array	†	weak	free		7.2.2
		Reorder Methods & Instance Variables	low	one-way	free		7.3
		Reorder Arrays	low	weak	free		7.3

FIG. 31a-2

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TARGET OPERATION	OBFUSCATION TRANSFORMATION	POTENCY	QUALITY		COST	METRICS	SECTION
			POTENCY	RESILIENCE			
Preventive Targeted Inherent	HoseMocha	low		trivial	free	$\mu 1$	9
	Add Aliased Formals to Prevent Slicing	medium		strong	free	$\mu 1, \mu 5$	9.4
	Add Variable Dependencies to Prevent Slicing	Depends on the quality of the opaque predicate.				$\mu 1$	9.4
	Add Bogus Data Dependencies	medium		weak	cheap	$\mu 1$	9.1.1
	Use Opaque Predicates with Side-Effects	medium		weak	free	$\mu 1$	9.5
	Make Opaque Predicates using Difficult Theorems	†		†	†	$\mu 1$	9.5

FIG. 31b

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OPAQUE CONSTRUCT	RESILIENCE	QUALITY		SECTION
			COST	
Created from calls to library functions.	trivial		Depends on the cost of the library function	6.1.1
Created from local (intra-basic block) information.	trivial		free ... cheap	6.1.1
Created from global (inter-basic block) information.	weak		free ... cheap	6.1.1
Created from inter-procedural and aliasing information.	full		cheap ... costly	8.1
Created from process interaction and scheduling	full		cheap ... costly	8.2

FIG. 32

INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 98/12017

A. CLASSIFICATION OF SUBJECT MATTER

IPC 6 G06F9/44 G06F1/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 97 04394 A (DRAKE CHRISTOPHER NATHAN) 6 February 1997 see page 3, line 25 - page 4, line 10 see page 5, line 25 - page 6, line 8 ---	1-20
A	COHEN F B: "OPERATING SYSTEM PROTECTION THROUGH PROGRAM EVOLUTION" COMPUTERS & SECURITY INTERNATIONAL JOURNAL DEVOTED TO THE STUDY OF TECHNICAL AND FINANCIAL ASPECTS OF COMPUTER SECURITY, vol. 12, no. 6, 1 October 1993, pages 565-584, XP000415701 see the whole document ---	1-20
P, A	WO 97 33216 A (NORTHERN TELECOM LTD) 12 September 1997 see page 8, line 13 - page 9, line 33 -----	1-20



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

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Date of the actual completion of the international search

15 September 1998

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Inter. .onal Application No

PCT/US 98/12017

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9704394 A	06-02-1997	AU 5945796 A	23-01-1997
WO 9733216 A	12-09-1997	US 5748741 A	05-05-1998